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Filmwise Condensation of Steam on Horizontal
Corrugated and Wire-Wrapped Corrugated Tubes

by

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Lieutenant, United States Navy
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Results obtained for steam condensation indicate that the MHT Korodense titanium tube provides negligible enhancement compared to the a titanium tube. The addition of wire-wrapping provided minimal increase in the outside heat transfer coefficient about 8% at a fractional coverage of approximately 5% corresponding to a pitch to wire diameter ratio near 20.

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ABSTRACT

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TABLE OF CONTENTS

I. INTRODUCTION 1

A. BACKGROUND 1

B. CONDENSATION APPLICATIONS FOR ENHANCED TUBES . 3

C. NAVAL POSTGRADUATE SCHOOL CONDENSATION RESEARCH 5

D. OBJECTIVES 6

II. LITERATURE SURVEY 7

A. INTRODUCTION 7

B. VAPOR SIDE CONSIDERATIONS 8

1. Horizontal Smooth Tubes 8

2. Wire-Wrapped Smooth Tubes 10

3. Corrugated Tubes 12

4. Wire-Wrapped Corrugated Tubes 16

C. COOLANT SIDE CONSIDERATIONS 17

1. Smooth Tubes 17

2. Corrugated Tubes 19

3. Tubes With Inserts 23

III. EXPERIMENTAL APPARATUS 25

A. SYSTEM OVERVIEW 25

B. SYSTEM INSTRUMENTATION 30

C. TUBES TESTED 31

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NAVAL POSTGRADUATE SCHOOL
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IV. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS 34

A. TUBE PREPARATION 34

B. SYSTEM START-UP AND SHUTDOWN PROCEDURES 35

C. DATA COLLECTION PROCEDURE 39

D. DATA REDUCTION PROCEDURE 39

E. MODIFIED WILSON PLOT TECHNIQUE 43

F. ENHANCEMENT RATIO 46

V. RESULTS AND DISCUSSION 48

A. HEAT TRANSFER CORRELATIONS 48

B. VERIFICATION AND REPEATABILITY OF RESULTS . . . 49

C. ANALYSIS OF CORRUGATED TUBE RESULTS 53

D. ANALYSIS OF WIRE-WRAPPED CORRUGATED TUBE RESULTS 59

VI. CONCLUSIONS AND RECOMMENDATIONS 79

A. CONCLUSIONS 79

B. RECOMMENDATIONS 79

APPENDIX A. SYSTEM CORRECTIONS 81

A. FRICTIONAL TEMPERATURE CORRECTIONS 81

APPENDIX B. UNCERTAINTY ANALYSIS 84

APPENDIX C. DRPML PROGRAM LISTING 90

LIST OF REFERENCES 122

INITIAL DISTRUBUTION LIST 129

LIST OF TABLES

Table I. LISTING OF TUBES TESTED 33

Table II. SMOOTH TITANIUM TUBE AT ATMOSPHERIC PRESSURE 54

Table III. SMOOTH TITANIUM TUBE AT VACUUM PRESSURE . 55

Table IV. 0.5 mm WIRE-WRAPPED SMOOTH TITANIUM TUBE WITH HEATEX INSERT 56

Table V. PLAIN LPD KORODENSE TUBE 57

Table VI. 0.5 mm WIRE-WRAPPED LPD KORODENSE TUBE WITH HEATEX INSERT 58

Table VII. 0.5 mm WIRE-WRAPPED SMOOTH COPPER TUBE WITH HEATEX INSERT 59

Table VIII. PLAIN MHT KORODENSE TUBE 60

Table IX. WIRE-WRAPPED AND PLAIN MHT KORODENSE TUBES 68

Table A. 1 FRICTIONAL TEMPERATURE RISE EQUATIONS FOR MHT KORODENSE TUBE 83

LIST OF FIGURES

Figure 1. Profile of a Corrugated Tube 3

Figure 2. Schematic of the Single Tube Test Apparatus 26

Figure 3. Schematic of the Test Section 27

Figure 4. Schematic of the Purging System and Cooling Water 29

Figure 5. h_o vs. ΔT_{cf} for a Plain MHT Korodense Tube Under Vacuum 50

Figure 6. h_o vs. ΔT_{cf} for a Smooth Titanium Tube Under Vacuum 51

Figure 7. h_o vs. ΔT_{cf} for a Smooth Titanium Tube at Atmospheric Pressure 52

Figure 8. h_o vs. ΔT_{cf} for a Smooth Titanium and a Plain MHT Korodense Tubes Under Vacuum 61

Figure 9. U_o vs. V_w for a Plain MHT Korodense Tube at Atmospheric Pressure 62

Figure 10. U_o vs. V_w for a Plain MHT Korodense Tube Under Vacuum 63

Figure 11. U_o vs. V_w for Wire-Wrapped MHT Korodense Tubes Under Vacuum with HEATEX Insert 64

Figure 12. h_o vs. ΔT_{cf} for Wire-Wrapped MHT Korodense Tubes Under Vacuum 65

Figure 13. h_o vs. ΔT_{cf} for Wire-Wrapped MHT Korodense Tubes Under Vacuum 66

Figure 14. Enhancement Ratio vs. P_w/D_W for Wire-Wrapped Korodense Tubes 69

Figure 15. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense Tubes 70

Figure 16. Enhancement Ratio vs. P_w/D_W for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes, NPS Data 72

Figure 17. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes, NPS Data 73

Figure 18. Enhancement Ratio vs. P_w/D_w for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes . . 75

Figure 19. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes 76

Figure 20. C_i vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes at Atmospheric Pressure 78

Figure A.1 Frictional Temperature Rise for the MHT Korodense Titanium Tube with and without a HEATEX Insert 82

NOMENCLATURE

a	as defined in equation (4.30)
A_i	effective inside surface area, m^2
A_o	effective outside surface area, m^2
b	as defined in equation (4.26)
c	as defined in equation (2.22)
c_p	specific heat at a constant pressure, J/kg-K
c_8	as defined in equation (2.14)
C_i	leading coefficient for the inside heat transfer correlation used
C_n	as defined in equation (2.8)
d	as defined in equation (2.23)
d_o	external groove diameter, m
D_i	tube inside diameter, m
D_o	tube outside diameter, m
D_w	wire diameter, m
e	groove depth, m
E_1	as defined in equation (2.32)
E_2	as defined in equation (2.33)
E_3	as defined in equation (2.35)
f	as defined in equation (2.30)
F	as defined in equation (2.4)
g	gravitational constant, 9.81 m/s
h_{fg}	specific enthalpy of vaporization, J/kg

h_i inside heat transfer coefficient, W/m^2-K

h_o outside heat transfer coefficient, W/m^2-K

h_{oe} outside heat transfer coefficient for enhanced tubes, W/m^2-K

h_{os} outside heat transfer coefficient for smooth tubes, W/m^2-K

k_c thermal conductivity of the coolant film, W/m-K

k_f thermal conductivity of the condensate film, W/m-K

k_m thermal conductivity of the tube material, W/m-K

K_1 as defined in equation (2.26)

K_2 as defined in equation (2.27)

L active length of tube exposed to steam, m

L_o external groove depth, m

L_1 length of inlet portion of tube, m

L_2 length of outlet portion of tube, m

LMTD log mean temperature difference, K

m Reynolds number exponent

$\dot{m}$ mass flow rate of the coolant, kg/s

m_1 as defined in equation (4.25)

n Prandtl number exponent

n_t number of tubes in a vertical row

Nu Nusselt number

P corrugation pitch, m

P_w wire-wrap pitch, m

P_{sat} saturation pressure, Pa

Pr Prandtl number

Pr_w Prandtl number at the wall temperature

PW as defined in equation (2.10)

Q heat transfer rate, W

q heat flux, W/m^2

r tube specific constant as defined for equation (2.30)

R radius of curvature of corrugation ridge, m

R_f fouling resistance, K/W

R_i inside thermal resistance, K/W

R_o outside thermal resistance, K/W

R_{total} total thermal resistance, K/W

R_w wall thermal resistance, K/W

Re Reynolds number

Re_f Reynolds number for the condensate film

$Re_{2\phi}$ two phase Reynolds number

T_{cf} temperature difference across the condensate film, K

ΔT_{cf} temperature difference across the film, K

T_m mean coolant bulk temperature, K

T_{sat} vapor saturation temperature, K

T_{wo} outside wall temperature, K

T_1 cooling water inlet temperature, K

T_2 cooling water outlet temperature, K

U_o overall heat transfer coefficient, W/m^2-K

U_∞ vapor velocity, m/s

V_w coolant velocity, m/s

x Reynolds number exponent in equation (4.15)

X as defined in equation (4.24)

Y as defined in equation (4.23)

Z as defined in equation (4.19 or 4.20)

Z^* as defined in equation (2.9)

Greek Symbols

α leading coefficient for the outside heat transfer correlation used

$\acute{\alpha}$ helix angle measured from the tube axis

β as defined in equation (2.37)

ϵ as defined in equation (2.25)

ϵ_T enhancement ratio based on ΔT for wire-wrapped smooth tubes

ϵ_{Tc} enhancement ratio based on ΔT for wire-wrapped corrugated tubes

γ as defined in equation (2.29)

Γ mass flow rate of condensate per unit length of horizontal condenser tube

μ_c dynamic viscosity of the coolant, kg/m-s

μ_f dynamic viscosity of the condensate film, kg/m-s

μ_w dynamic viscosity of condensate at the wall, kg/m-s

η surface efficiency

Φ_c as defined in equation (2.14)

ω tube specific constant as defined for equation (2.10)

Ω as defined in equation (4.15, 4.16 or 4.17)

ρ_f density of the condensate film, kg/m^3

ρ_v density of the vapor, kg/m^3

σ_f surface tension of the condensate at film temperature, lb_f/ft

θ severity factor

θ^* tube specific constant as defined for equation (2.9)

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I. INTRODUCTION

A. BACKGROUND

Reductions in size, weight and cost have become increasingly important design considerations in the development of every component destined for use aboard United States Navy vessels. Significant reductions in weight have already been achieved for main propulsion machinery with the advent of the gas turbine propulsion plant. Weight reduction is also possible through redesign of auxiliary systems and other large components such as main steam condensers. The use of heat transfer enhancement techniques for condenser tubing has been one avenue receiving considerable attention in the pursuit of this goal. Smaller more efficient condensers would result in reductions in capital cost, space requirements, weight and operating cost.

The four primary factors that affect the performance of condensers are the thermal resistances on the coolant side, across the tube wall, the vapor side, and also that due to fouling. Each can be reduced to minimize its effect, which in turn enhances the overall heat transfer rate of the system. In experimental studies, the fouling resistance can be neglected if the tube is thoroughly clean prior to testing.

Enhancement techniques can be categorized into two major groups, active and passive. Guido [Ref. 1] compiled a fairly comprehensive listing of both groups of enhancement techniques for the tube side heat transfer rate. Passive techniques such as internal helical ribbing and displaced promoters (the use of wire mesh or HEATEX inserts) will be discussed in detail in a later section. It should be noted, however, that both of these techniques have a corresponding increase in pumping power requirements. Wall thermal resistance can be reduced passively by decreasing the wall thickness or changing the tube material. Similar to enhancement techniques for the tube side, the shell side resistance can also be reduced by both active and passive means. The passive enhancement techniques of wire-wrapping and tube corrugation will also be covered in a later section.

A variety of corrugated or roped tubes are available for use in condenser applications. Figure 1 shows the profile of one type of corrugated tube which has a groove radius smaller than the ridge radius. Wolverine Tube Company manufactures a low pressure drop (LPD) and a maximum heat transfer (MHT) tube of this type (trade name: Korodense), available for commercial use. The MHT tubes have a larger groove depth compared to the LPD tubes [Ref. 2]. Other types of corrugated tubes are also available which have a larger groove radius than the ridge radius. Marto et al. [Ref. 3] present test results on various other corrugation geometries.

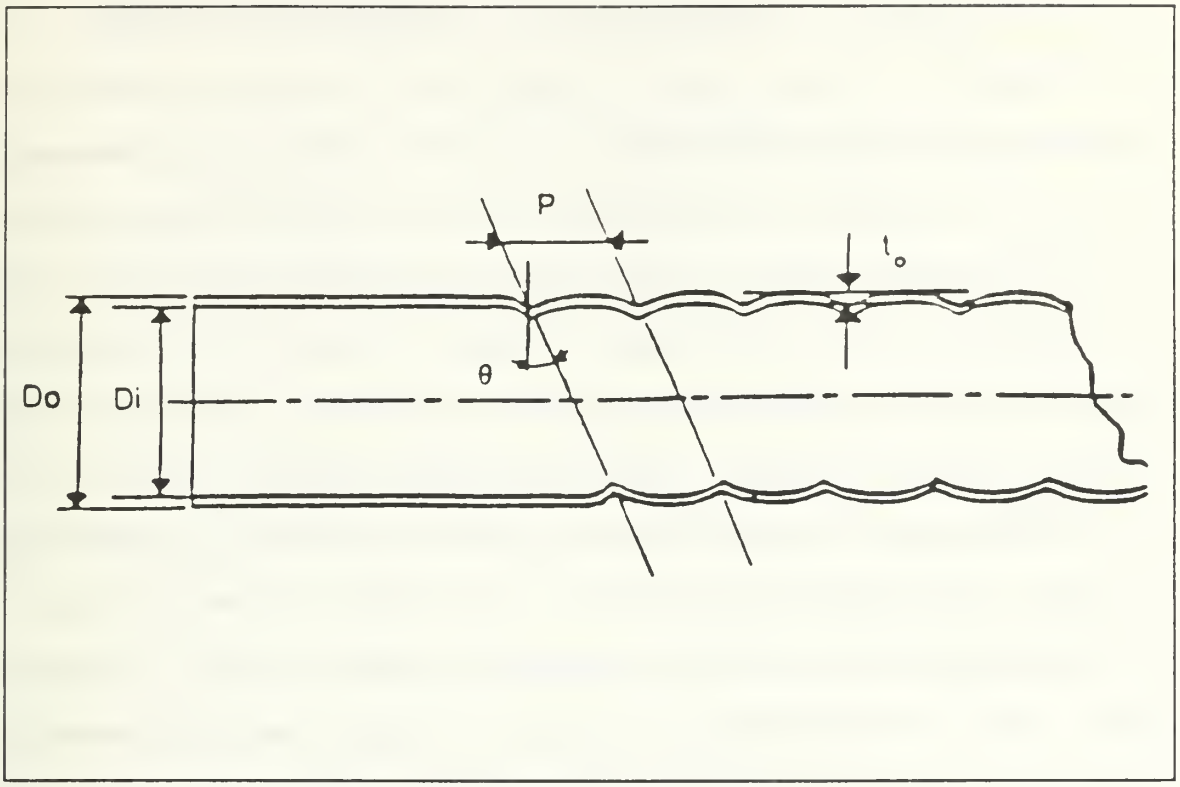

Figure 1. Profile of a corrugated tube

B. CONDENSATION APPLICATIONS FOR ENHANCED TUBES

In 1971 Withers and Young [Ref. 4] performed a theoretical analysis on a power plant main condenser. Their findings indicated a substantial saving in almost every condenser aspect if the smooth tubes were replaced by Korodense roped tubes. Similar results were obtained by Webb et al. [Ref. 5]. They indicated a possible 30 to 40 percent increase in the overall heat transfer coefficient when analyzing a tube-for-tube replacement of smooth to Korodense tubes. This benefit was calculated for two separate power plants of different heat duty. An ongoing comprehensive study of 14 Tennessee Valley

Authority (TVA) power plant condensers, retubed with corrugated tubes, has yielded significant economic and performance benefits [Refs. 6 and 7]. Of the 14 condensers retubed by TVA, their Gallatin Unit 1 has provided long-term results with over 12 years of successful operation since retubing. In 1983 Boyd et al. [Ref. 8] studied the performance of TVA's Gallatin Unit 1 plant after only three years of operation. Their findings yielded up to a 43% increase in the overall heat transfer coefficient when clean tubes were analyzed. However, data also indicated that the corrugated tubes fouled quicker than plain tubes. Rabas et al. [Ref. 9] studied 12 of the retubed TVA condensers and found fouling rates for the enhanced tubes ranging from about the same as to almost twice that experienced in plain tubes. Although the fouling rates were higher, Rabas et al. [Ref. 9] reported the fouling resistance values for the LPD Korodense tubes never exceeded the minimum allowable TEMA standard.

Union Carbide [Ref. 10] performed analysis on roped condenser tubes with a Thin Film Condensing Promoter (T.F.C.P.), which is essentially a wire-wrapped roped tube. Their findings indicated an increase in the heat transfer coefficient by a factor of between 2 to 3 times that found with a smooth tube under condensate loaded conditions.

C. NAVAL POSTGRADUATE SCHOOL CONDENSATION RESEARCH

Titanium has a number of properties which make it a desirable alternative to the conventional copper-nickel tubing currently in use today on board Naval vessels. Its high strength to weight ratio enables the tubes to be designed with a much thinner wall thickness, while still maintaining the durability of the overall system. Titanium also has a high resistance to erosion and sea water corrosion. This leads to reduced shutdown time for tube cleaning and replacement. One of the primary disadvantages of titanium tubing is its poor thermal conductivity. Titanium has approximately 50% the thermal conductivity of copper-nickel [Ref. 11]. This disadvantage can be partially offset by a decreased wall thickness and also through the use of enhanced surfaces. The Naval Postgraduate School (NPS), in conjunction with the Naval Surface Warfare Center, Carderock Division, Annapolis Detachment, has been testing the enhancement characteristics of various types of titanium tubing.

In order to examine the heat transfer characteristics of various types of enhanced tubes, a suitable test platform must be utilized. While the ideal test platform would be a full scale model of the actual condenser used in the field, the cost associated with such an apparatus would be prohibitive. The condensation test platform, constructed by Krohn [Ref. 12] at NPS, has been in use since 1982. Although several modifications have been made by various researchers since that

time, the overall apparatus and the operation remain basically unchanged. Van Petten [Ref. 13] lists a comprehensive summary of the work completed by eight NPS researchers from 1982 through 1987. Most of the work concentrated on the performance of various types of externally finned tubes. Mitrou [Ref. 14], in addition to studying finned tubes, also performed experiments on wire-wrapped smooth copper tubes. More recent work conducted by Coumes [Ref. 15], Guttendorf [Ref. 16] and Swensen [Ref. 17] dealt with further studies of finned copper tubes. O'Keefe [Ref. 18] studied the performance of various titanium tubes. His tests included smooth tubes, wire-wrapped smooth tubes, LPD Korodense tubes, and wire-wrapped LPD Korodense tubes. Other researchers including Kanakis, Brower and Mazzone [Refs. 19-21] have studied tube bundle configurations for smooth and corrugated tubes, both with and without wire-wrapping.

D. OBJECTIVES

The main objectives of this study are as follows:

1. To verify the repeatability of the calculated coefficients for both coolant side and vapor side heat transfer correlations obtained by previous researchers on wire-wrapped smooth and corrugated titanium tubes.
2. To manufacture and collect condensation data on smooth and MHT Korodense titanium tubes with varying fractional coverage due to wire-wrapping.
3. To determine if any relationship exists for optimal fractional coverage or pitch to diameter ratio between wire-wrapped smooth tubes and wire-wrapped MHT and LPD Korodense tubes.

II. LITERATURE SURVEY

A. INTRODUCTION

Condensation on horizontal tubes has been an intensely studied heat transfer mechanism throughout the years. New developments in condenser tubing require continued experimental and theoretical research in this field.

There are two fundamental modes of condensation on horizontally mounted condenser tubes, filmwise and dropwise. Dropwise condensation can produce heat transfer rates as much as an order of magnitude larger than those associated with filmwise condensation. Various surface coatings have been developed in order to promote dropwise condensation and take advantage of the higher heat transfer rates. However, with time these coatings lose their effectiveness and filmwise condensation eventually returns. For this reason, condenser design calculations are normally based on the more conservative filmwise mode of condensation [Ref. 22].

Internally, the primary factors affecting thermal resistance are the intensity of turbulence and the thermal conductivity of the coolant medium. The degree of turbulence can be changed by altering the internal tube wall geometry or through the use of displacement promoters.

B. VAPOR SIDE CONSIDERATIONS

Condensation on horizontal tubes consists of a complex two phase process. A suitable theoretical model must be utilized in order to accurately predict these phenomena.

1. Horizontal Smooth Tubes

Nusselt [Ref. 23] developed the foundation for the study of filmwise condensation on horizontal tubes in 1916. His work was formulated for a quiescent vapor condensing on a single horizontal tube. Due to the increase in the thickness of condensate as gravity forces it around the sides of the tube, the local heat transfer coefficient decreases around the tube circumference. Nusselt developed a theory for the average heat transfer coefficient around the tube, accounting for the lower resistance at the top of the tube where the film was the thinnest and the higher resistance at the bottom of the tube where the film was the thickest. As a result, he developed the following equation:

$$h_o = 0.728 \left[\frac{k_f^3 \, g \, \rho_f \, (\rho_f - \rho_v) \, h_{fg}}{\mu_f \, D_o \, (T_{sat} - T_{wo})} \right]^{1/4} \qquad (2.1)$$

where the fluid properties are evaluated at the film temperature, given by:

$$T_f = \frac{1}{3} T_{sat} + \frac{2}{3} T_{wo} \qquad (2.2)$$

Nusselt's theory has been extensively studied since 1916, and with the imposed assumptions, has been found to be

generally valid [Refs. 24, 25]. It has also been found to be accurate for cases which do not conform to Nusselt's original assumptions, such as variable wall temperature [Ref. 26]. One of the major problems encountered in applying Nusselt's theory in the design of condensers arises from his assumption of a quiescent vapor. While in theory, and in some limited practical applications, the assumption of a stationary vapor can be justified, most steam condensers operate under conditions where the vapor is travelling at some constant velocity.

With the vapor in motion, sufficient shear forces can be developed which significantly thin the condensate film and increase the outside heat transfer coefficient. Early theoretical work by Shekriladze and Gomelauri [Ref. 27], which accounted for vapor shear, resulted in the following equation to approximate the mean Nusselt number.

$$\frac{Nu}{Re_{2\phi}^{1/2}} = 0.64(1+(1+1.69F)^{1/2})^{1/2} \qquad (2.3)$$

where:

$$F = \frac{g\, D_o\, \mu_f\, h_{fg}}{U_\infty^2\, k_f\, (T_{sat}-T_{wo})} \qquad (2.4)$$

and the two phase Reynolds number is given by:

$$Re_{2\phi} = \frac{\rho_f\, U_\infty\, D_o}{\mu_f} \qquad (2.5)$$

Lee and Rose [Ref. 28] compared vapor shear models with experimental results and found that the Shekriladze-Gomelauri results were more conservative than more rigorous developments performed by other researchers due to their simplified approximation for the interfacial shear stress. Fujii et al. [Ref. 29], in a more recent study, performed an extensive development on the outside of a horizontal tube. From experimental data, they also developed an empirical formulation for the condensation of steam on a horizontal tube which includes vapor velocity effects:

$$\frac{Nu}{Re_{2\phi}^{1/2}} = 0.96\ F^{1/5} \qquad (2.6)$$

where F and $Re_{2\phi}$ are defined in equations (2.4)and (2.5). For situations where the surface shear forces dominate, equation (2.6) tends to more accurately predict the vapor side heat transfer coefficient for steam.

As discussed previously, the primary modes of external tube enhancement covered in this study are wire-wrapping and the addition of helical grooves. Both methods have associated advantages and disadvantages.

2. Wire-Wrapped Smooth Tubes

The benefits of wire-wrapping smooth tubes have been attributed to two primary effects: the thinning of the condensate film between the wires due to surface tension forces and the better drainage of the condensate along the

wire, (Fujii et al. [Ref. 30] and Marto et al. [Ref. 31]). Thomas [Ref. 32] conducted tests on vertical tubes with wires attached vertically along the tubes and demonstrated this latter enhancement effect. Horizontal smooth tubes with coiled wire were later studied by Thomas et al. [Ref. 33] and their findings indicated a two fold increase in the heat transfer coefficient over that predicted by Nusselt theory for a smooth tube. Marto et al. [Ref. 31] determined an optimum wire pitch to diameter ratio between 5 and 7 for steam condensation. They achieved an enhancement between 1.5 and 1.8 for the heat transfer coefficient over plain tubes.

For low surface tension fluids (R-11 and ethanol), Fujii et al. [Ref. 30] obtained results 2 to 3 times those predicted by Nusselt theory, with an optimum wire pitch to diameter ratio of 2. O'Keefe [Ref. 18] compared the enhancement ratio versus fractional coverage (the percentage of the tube's surface covered by wire) on a titanium smooth tube. Together with data obtained by Mitrou [Ref. 14] and Sethumadhavan and Rao [Ref. 34], he determined that the optimum fractional coverage was between 10 and 30%. This fairly broad range of values was attributed to the possible effects of the different tube material thermal conductivities used in the studies.

3. Corrugated Tubes

In 1971, Withers and Young [Ref. 35] performed a design study of two condenser bundles with heat duty of 25 million Btu/hr, one with bare (smooth) tubes and the other with corrugated (roped) tubes. Coolant flow pressure drop was one of the matching parameters for the comparison. This requirement made it necessary to use a larger corrugated tube (1.00 inch outside diameter (OD)), than the smooth tube (0.75 inch OD). They found an enhancement of 88% for the outside bundle heat transfer coefficient. Catchpole and Drew [Ref. 36] tested single corrugated tubes and determined that the steam side heat transfer coefficient increased with increasing groove density and passed through a maximum with increasing groove depth. Their conclusion was that the smaller the helix angle (measured from the tube axis), the worse the condensate drainage, resulting in a reduction of the outside heat transfer coefficient. Similar results were reported by Marto et al. [Ref. 3] and Mehta and Rao [Ref. 37]. Eleven different corrugated tubes of three primary types were tested by Marto et al. [Ref. 3]. Within each corrugation type, the largest value for the outside heat transfer coefficient was obtained at small pitch to diameter ratios (P/D). As P/D increased, the enhancement ratio decreased. In tests conducted by Mehta and Rao [Ref. 37], they found the condensing coefficient enhancement ratio decreased from 1.26 to 1.1 when the corrugation groove pitch was increased from 6.35 mm to 12.5 mm

with a constant groove depth of 0.63 mm. They also tested the effect of holding the groove pitch to groove depth ratio constant. A maximum enhancement ratio of 1.38 was achieved with the smallest groove depth and pitch. Zimparov et al. [Ref. 38] confirmed the same trend, using 27 mm outside diameter corrugated tubes, with the enhancement ratio increasing from 0.99 to 1.22 for a corrugation groove pitch decreasing from 16.9 mm to 6.5 mm.

Cunningham and Bahjernejad [Ref. 39] examined the effects of condensate inundation on corrugated tube bundles. They tested two different multistart tubes, one with two helical starts and the other with six starts. Their results indicated severe limitations in performance due to inundation effects for tube bundles more than a few rows deep. Additional inundation tests were conducted on multistart tubes by Cunningham and Boudinar [Ref. 40]. They reported similar results as those of Cunningham and Bahjernejad [Ref. 39], and additionally found that the more severe the indentation (groove depth) on the roped tube, the greater was the reduction in vapor side heat transfer for the tube bundle.

Rabas [Ref. 41] studied an extensive data bank of results published by numerous researchers. He found that the enhancement in the outside heat transfer coefficient was negligible for tubes with grooved geometries that are suitable

for ball cleaning[1] of the inside surface. He also compared the collected data with the results predicted by three different correlations. The Wolverine correlation [Ref. 2]:

$$h_o = 0.725\ C_n \left[\frac{k_f^3\ \rho_f^2\ g\ h_{fg}}{n_t\ \mu_f\ D_o\ (T_{sat}-T_{wo})} \right]^{1/4} \qquad (2.7)$$

where:

$$C_n = Z^*\ [n_t]^{PW} \qquad (2.8)$$

$$Z^* = 38\ (\sigma_f)^{0.65} + \frac{\theta^*}{\mu_f} \qquad (2.9)$$

and:

$$PW = \left[(5.31E\text{-}7) + \left[0.195\ (\omega)^{0.932/\mu_f} \right]^6 \right]^{1/6} \qquad (2.10)$$

- Values for ω and θ^* are listed for specific tube geometries by Wolverine in Reference 2.
- The variable C_n in Equation (2.7) must be applied using English units.

and the correlation developed by Mehta and Rao [Ref. 37]:

$$\frac{h_o}{(k_f^3\ \rho_f^2\ g/\mu_f^2)^{1/3}} = 1.54\ e^{205\theta} \left(\frac{4\Gamma}{\mu_f} \right)^{-0.33e^{-7.5\theta}} \qquad (2.11)$$

for $0 < \theta < 15 \times 10^{-4}$, and:

---

[1]ball cleaning is a method of removing deposits from the inside of condenser tubes by periodically recirculating sponge rubber balls through the tubes with the coolant.

$$\frac{h_o}{(k_f^3\ \rho_f^2\ g/\mu_f^2)^{1/3}} = 1.92\ e^{-13.20\Theta}\left(\frac{4\Gamma}{\mu_f}\right)^{-0.33e^{-7.50\Theta}} \qquad (2.12)$$

for $15x10^{-4} < \Theta < 200x10^{-4}$, were both found to overpredict the outside heat transfer coefficient. Values similar to those obtained from the experimental data were predicted by the Yorkshire correlation [Ref. 42] given by:

$$h_o = C_8\left[\frac{k_f^3\ \rho_f^2\ g}{\mu_f\ \Gamma}\right]^{1/3} \qquad (2.13)$$

where:

$$C_8 = 1 + \Phi_c\left[\frac{L_o}{D_o}\right]\left[\frac{P}{D_o}\right]^{-0.75} \qquad (2.14)$$

and Φ_c varies with tube profile and can be found in Reference 42. However, Rabas [Ref. 41] cautioned its use due to the results being close to unity. In conclusion, he recommended using smooth tube correlations and neglecting the minimal enhancement associated with corrugated tubes for design calculations.

Dreitser et al. [Ref. 43] determined a correlation for the enhancement ratio of corrugated tubes based on three primary geometric ratios: 1) The ratio of the radius of curvature of the corrugation ridge to the outside diameter, R/D_o; 2) the ratio of groove pitch to the outside diameter, P/D_o; and 3) the ratio of the external groove diameter to the outside diameter, d_o/D_o.

$$\frac{h_{oe}}{h_{os}} = 2.469\left(1-0.2445\frac{R}{D_o}\right)\left(1-0.379\frac{P}{D_o}\right)\exp\left[3.65\left(1-\frac{d_o}{D_o}\right)\right] \quad (2.15)$$

They found that if any of the three ratios were increased while keeping the others constant, the enhancement ratio would decrease.

Cunningham and Fidler [Ref. 44] made a comparative study of the effects of vapor shear on multistart corrugated tubes and smooth tubes. They found that the corrugated tubes maintained their enhancement advantage over the smooth tube when subjected to increased vapor velocity.

4. Wire-Wrapped Corrugated Tubes

Wire-wrapping of corrugated tubes has been shown by various researchers to significantly reduce the effect of condensate inundation (Memory et al. [Ref. 45], Union Carbide [Ref. 10], and Marto and Wanniarachchi [Ref. 46]).

Union Carbide [Ref. 10] tested steam condensation for a wire-wrapped roped tube in a bundle arrangement. They reported nearly identical performance for both the unloaded and the condensate loaded conditions tested. Condensing coefficients approximately 2.5 times that of plain tube results were achieved for the condensate loaded condition. Memory et al. [Ref. 45] obtained a 60 to 68% enhancement over smooth tube results when condensing R-113 on a wire-wrapped roped tube bundle arrangement containing four tubes in a

vertical column. Their tests indicated an optimal wire pitch to diameter ratio of 7.5.

O'Keefe [Ref. 18] tested the enhancement effects of three different wire diameters (1.6 mm, 1.0 mm, and 0.5 mm) when used to wrap an LPD Korodense tube. Enhancements ranging between 20 and 30% above smooth tube results were obtained with the maximum obtained for the 0.5 mm wire with a wire pitch to wire diameter ratio of 14.

C. COOLANT SIDE CONSIDERATIONS

1. Smooth Tubes

Numerous correlations have been developed for use in the analysis of the coolant side heat transfer correlation associated with the turbulent flow regime inside a pipe (Re > 10,000). Many of the earlier correlations have been presented in the form:

$$Nu = C_i Re^m Pr^n \qquad (2.16)$$

This form has been used for several well-known correlations including those developed by Dittus and Boelter [Ref. 47]:

$$Nu = 0.023\ Re^{0.8} Pr^{0.4} \qquad (2.17)$$

and Colburn [Ref. 48]

$$Nu = 0.023\ Re^{0.8} Pr^{1/3} \qquad (2.18)$$

A correction factor for equation (2.18) was developed by Sieder and Tate [Ref. 49]:

$$Nu = 0.027\ Re^{0.8} Pr^{1/3} (\mu_c/\mu_w)^{0.14} \qquad (2.19)$$

This modification compensates for the variation in the coolant viscosity when large temperature differences exist between the bulk coolant and the inner tube wall temperature. All fluid properties for equations (2.17), (2.18), and (2.19) are evaluated at the mean coolant bulk temperature, T_m.

$$T_m = \frac{(T_1 + T_2)}{2} \qquad (2.20)$$

In more recent years, Sleicher and Rouse [Ref. 50] and Petukhov [Ref. 51] developed equations (2.21) and (2.24) respectively, which are applicable over a wider range of Prandtl numbers.

$$Nu = 5 + 0.015\ Re_f^{\,c}\ Pr_w^{\,d} \qquad (2.21)$$

where:

$$c = 0.88 - \frac{0.24}{4 + Pr_w} \qquad (2.22)$$

$$d = \frac{1}{3} + 0.5 \exp(-0.6\ Pr_w) \qquad (2.23)$$

and,

$$Nu = \frac{(\varepsilon/8)\ Re\ Pr}{K_1 + K_2(\varepsilon/8)^{1/2}\ (Pr^{2/3}-1)} \qquad (2.24)$$

where:

$$\varepsilon = (1.82 \log(Re) - 1.64)^{-2} \quad (2.25)$$

$$K_1 = 1 + 3.4\varepsilon \quad (2.26)$$

$$K_2 = 11.7 + 1.8\, Pr^{-1/3} \quad (2.27)$$

Lorenz et al. [Ref. 52] compared their experimental results for cold water (i.e. large Prandtl number) with seven of the more common inside heat transfer correlations. They found that the Petukhov-Popov and Sleicher-Rouse correlations agreed to within 5% of the experimental data. The other correlations typically underpredicted the data by between 5 and 15%.

2. Corrugated Tubes

The internal ridges of the tube wall produced when manufacturing corrugated tubes cause two primary effects. The irregularity of the wall surface results in an increased frictional effect and causes the flow to swirl, thereby requiring additional pumping power to achieve flow rates equal to similar diameter smooth tube flow. The increase in turbulence also has the effect of increasing the inside heat transfer rate. In the study by Withers and Young [Ref. 35], the total inside enhancement ratio of the tube bundle tested was 56% above that obtained for a smooth tube bundle designed with an equal pressure drop. Catchpole and Drew [Ref. 36] found the inside heat transfer coefficient to increase with increasing groove depth and groove frequency. However, they

stressed that the increase in performance was obtained at the expense of significantly greater friction factors and therefor increased pumping power and operating cost. In comparing their results with the Prandtl analogy [Ref. 53] they found that, due to the turbulence caused by the presence of grooves, the inside heat transfer coefficient followed the trend predicted by the Prandtl analogy.

Mehta and Rao [Ref. 37] presented their findings in terms of the severity factor, the ratio of groove depth squared to the product of groove pitch and inside diameter. This dimensionless group was chosen because it has been found to be a useful criterion for evaluation of heat transfer and frictional characteristics of plain and spirally enhanced tubes. An improvement of 260% was obtained above smooth tube results with the higher inside heat transfer coefficient corresponding to higher severity factors. Of the eleven tubes tested by Marto et al. [Ref. 3], inside enhancement was reported for all the tube geometries examined, with the magnitude ranging from 1.6 to 5.1 times a smooth tube. Zimparov et al. [Ref. 38] tested nine tubes with differing corrugation geometries and obtained results similar to previous researchers. They achieved inside enhancement ratios between 1.77 and 2.73, with an increase in the friction factor of 2 to 4 fold.

For corrugated tubes, Withers [Ref. 54] modified existing correlations and developed the following:

$$Nu = \frac{\sqrt{f/8}\ Re\ Pr}{7.22(P/D_i)^{-1/3}\sqrt{Pr}\left[(e/D_i)Re\sqrt{f/8}\right]^{0.127}+\gamma} \qquad (2.28)$$

where:

$$\gamma = -\left[2.5\ \ln\left(2\frac{e}{D_i}\right) + 3.75\right] \qquad (2.29)$$

and:

$$\sqrt{\frac{f}{8}} = -\frac{1}{2.46\ \ln[r + (7/Re)^m]} \qquad (2.30)$$

The variables m and r were determined for each tube by a curve-fitting procedure. He obtained agreement between experimental and predicted data to within 10%. Wolverine currently utilizes a form of this correlation in their Engineering Data Book II [Ref. 2].

In a comparison of the LPD and MHT Korodense tubes manufactured by Wolverine [Ref. 2], they report a 25% higher inside heat transfer coefficient for the MHT Korodense tube than for the LPD Korodense tube. The MHT Korodense tube also has twice the pressure drop of the LPD Korodense tube.

After compiling an extensive collection of published data, Rabas et al. [Ref. 55] recommended a minor modification to the leading coefficient in the Yorkshire correlation [Ref. 42] to better fit the experimental data. The Yorkshire correlation is similar in form to equation (2.17) with an

additional complex leading coefficient (E_1) to compensate for the corrugation tube geometry.

$$Nu = 0.027\ E_1\ Re^{0.8}\ Pr^{0.4} \tag{2.31}$$

where:

$$E_1 = 1.0 + 1.182\ E_2\ E_3/(P/D_i)^{0.7} \tag{2.32}$$

$$E_2 = \cos(\dot{\alpha}) \tag{2.33}$$

$$\dot{\alpha} = \tan^{-1}(P/\pi D_i) \tag{2.34}$$

$$\ln(E_3) = -\sum_{j=0}^{3} a_j[\ln(e/D_i)]^j \tag{2.35}$$

and:

$$a_0 = 5.0766,\quad a_1 = 4.4224,\quad a_2 = 1.1240,\quad a_3 = 6.700x10^{-2}$$

The modification by Rabas et al. [Ref. 55] changed the exponent in equation (2.32) from 0.7 to 0.406.

Panchal and France [Ref. 56] conducted a study of large pitch spirally indented tubes for possible application to pressure drop sensitive systems. Their data resulted in internal enhancements as high as 100% over smooth tube data and they reported agreement within a 20% error band for the results predicted by the correlation proposed by Mehta and Rao [Ref. 57], given by:

$$Nu = \frac{\sqrt{f/2}\ Re\ Pr}{\beta\ Pr^{0.55}(Re\sqrt{f/2})^{0.11} + \gamma} \qquad (2.36)$$

where:

$$\beta = 9.4(P/D_i)^{-0.15}(e/D_i)^{0.11} \qquad (2.37)$$

and γ is defined as in equation (2.29). It should be noted that β in equation (2.37) is constant for any given tube configuration.

3. Tubes With Inserts

Numerous types of inserts are available for use in enhancing the inside heat transfer coefficient. Some of the types used by previous researchers at NPS include: twisted tape, wire-wrap, and HEATEX (a wire mesh insert supplied by CAL GAVIN). A number of correlations have been developed for determining the inside heat transfer coefficient when using these various inserts [Refs. 58-60]. These correlations for HEATEX, however, are for specific loop densities of the wire matrix and are not universally valid. HEATEX inserts not only significantly increase the overall heat transfer rates, but also inhibit fouling. Gough and Rogers [Ref. 61] presented results collected from a condenser fitted with HEATEX inserts which was in operation for over four years without being shut down for cleaning. Their findings indicated the actual fouling resistance was over 96% less than the allowable limits after a service life of 26 times that of the original unit

with no insert. However, it should be noted that the use of an insert has a pronounced effect on increasing the pressure drop across the tube. Inserts are used in experimental applications to realize a larger temperature drop in the coolant flow, thus decreasing the uncertainty of the heat transfer calculations.

III. EXPERIMENTAL APPARATUS

A. SYSTEM OVERVIEW

The apparatus used for this research was originally constructed by Krohn [Ref. 12]. The initial design has been modified by several previous researchers (in particular Swensen [Ref. 17]) and has been used successfully by Coumes [Ref. 15], Guttendorf [Ref. 16], Swensen [Ref. 17] and O'Keefe [Ref. 18] to test condensation on single horizontal tubes of various configurations. Figure 2 contains a general schematic of the overall system. The boiler, a 0.30 meter diameter Pyrex glass cylinder, contains ten 4 kW, 440 Volt Watlow immersion heaters which are used to generate steam from distilled water. From the boiler, steam passes up through a cylindrical section of Pyrex glass with an inside diameter of 0.15 meters and a length of 2.13 meters. Two 90 degree Pyrex glass elbows redirect the steam back down a second similar cylindrical section of 1.52 meters in length. The steam then enters the stainless steel test section containing the horizontal condenser tube mounted as shown in Figure 3. The test section also contains a circular glass viewing port so the condensation process can be observed while conducting tests. Excess steam, not condensed on the sample tube, passes through the test section and into the final Pyrex glass

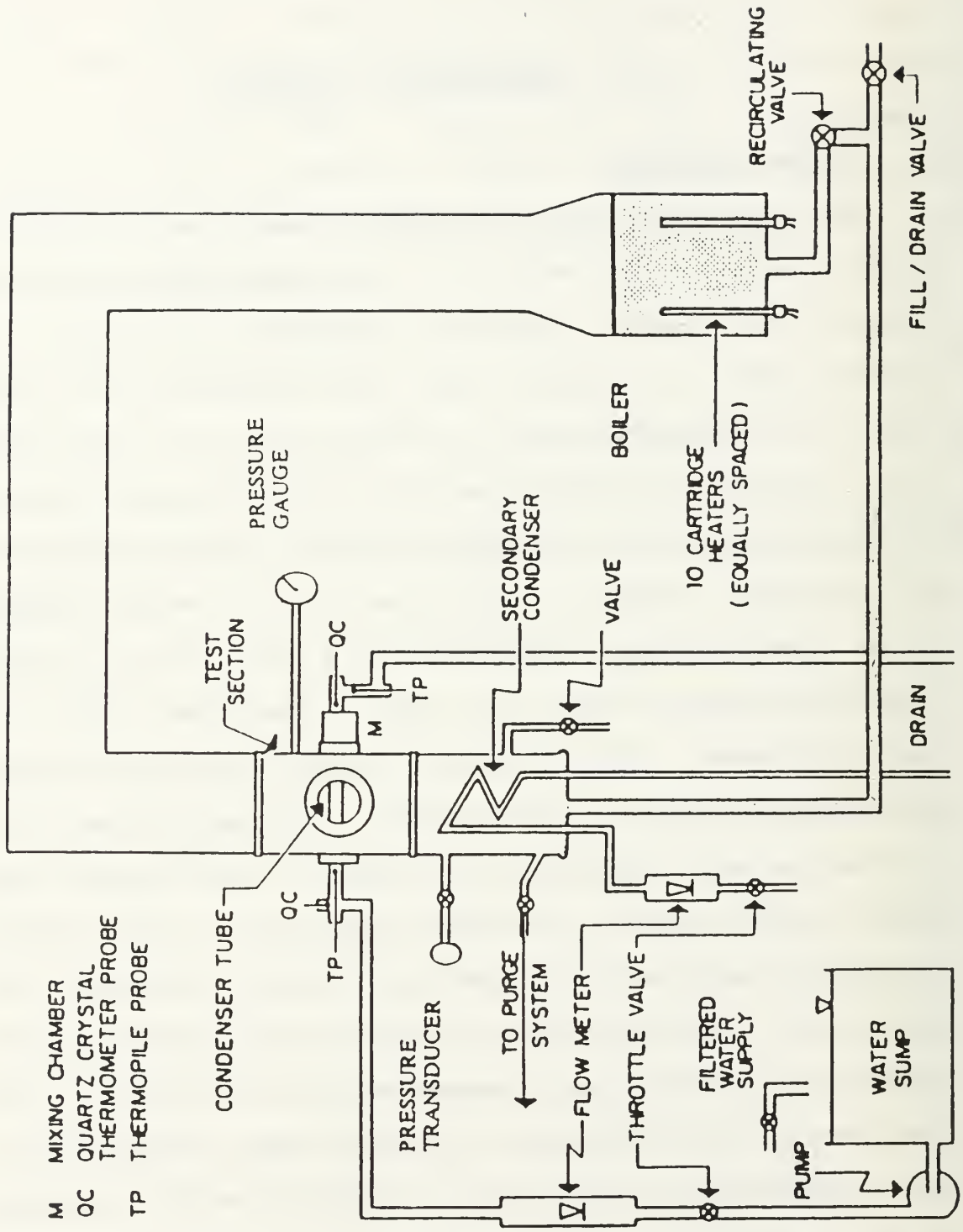

Figure 2. Schematic of the Single Tube Test Apparatus

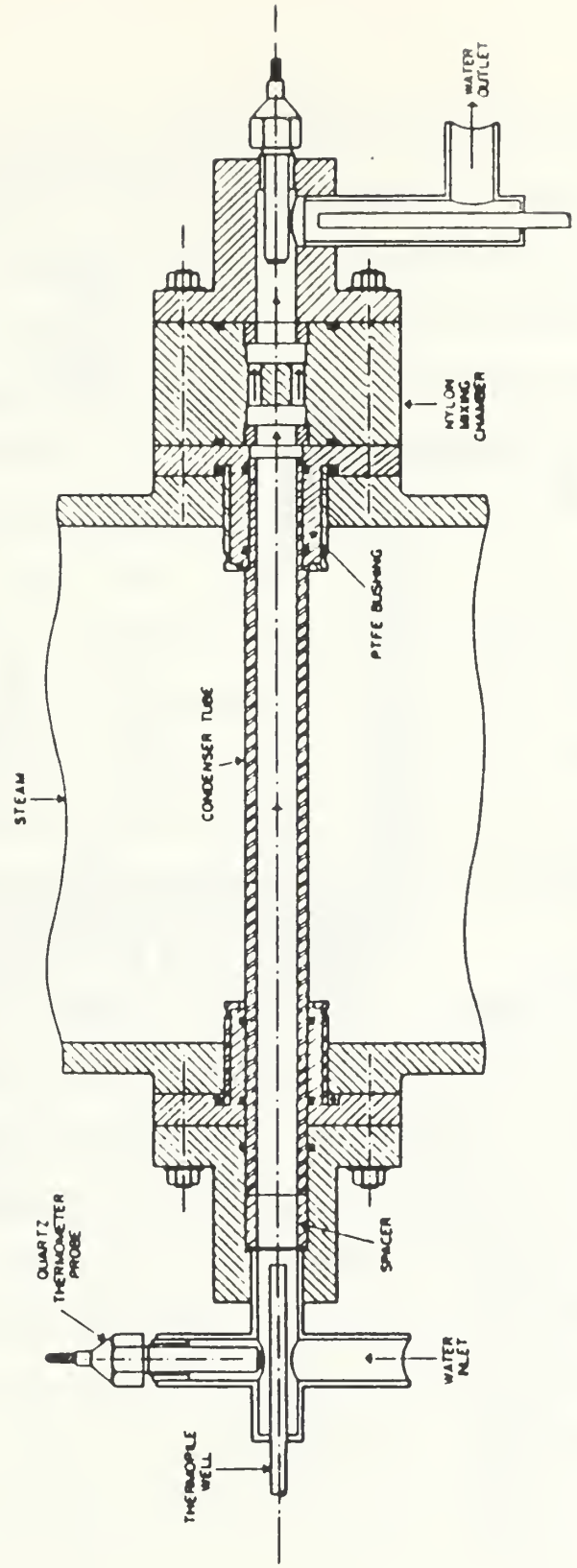

Figure 3. Schematic of the Test Section

cylinder containing an auxiliary condenser. The auxiliary condenser section collects all the condensate, where it returns to the boiler via a gravity drain in the baseplate.

Cooling water for the single horizontal tube in the test section was supplied by two centrifugal pumps connected in series and drawing suction from an adjacent cooling water sump. A throttling valve and calibrated flowmeter allowed for control of the cooling water flow rate. The auxiliary condenser cooling water was supplied directly from the building water main. After setting the desired coolant flow rate through the single horizontal tube, the saturation temperature in the test section was controlled by adjusting the throttle valve on the auxiliary condenser coolant flow line.

A suction port at the base of the auxiliary condenser section allowed for the removal of non-condensible gases. Figure 4 shows a schematic of the associated system. Non-condensibles drawn from the auxiliary condenser passed through an internal condensing coil where, any associated steam that might be present was condensed and collected in a plexiglass vacuum chamber for later removal. The non-condensibles then passed through the vacuum pump and were expelled to the atmosphere.

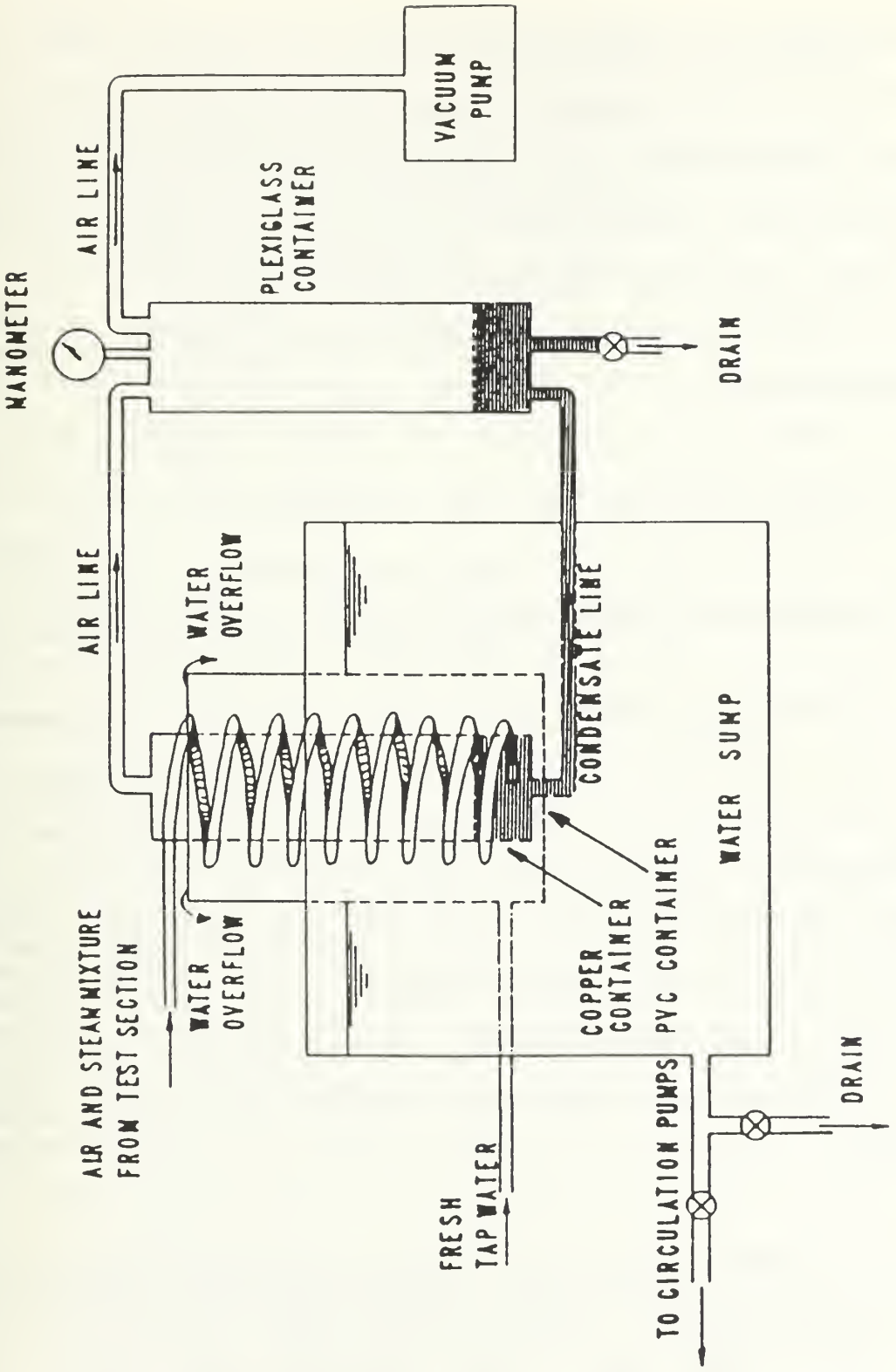

Figure 4. Schematic of the Purging System and Cooling Water

B. SYSTEM INSTRUMENTATION

The 440 Volt immersion heater power supply was controlled by a silicon controlled rectifier mounted on the electrical switchboard. Poole [Ref. 62] details the power calculation for the input into the data acquisition system.

Three separate methods were used to monitor the pressure of the system:

1. Setra model 204 pressure transducer.
2. System saturation temperature converted into pressure.
3. Heise solid front pressure gage (visual reference only).

Temperature measurements were obtained using several devices. The vapor temperature of the system was measured by a Teflon coated and a metal sheathed type-T copper/constantan thermocouple located just upstream of the horizontal tube being tested. Condensate return and ambient temperatures were also measured with Teflon coated type-T copper/constantan thermocouples. The inlet and outlet coolant temperature of the condenser test tube were measured with three separate probes:

1. A Teflon coated type-T copper/constantan thermocouple.
2. A ten junction, Teflon coated type-T copper/constantan thermopile.
3. An HP 2804A quartz crystal thermometer.

The three temperature probes at the outlet of the horizontal tube were located downstream of a mixing chamber in order to obtain a representative average coolant discharge temperature. Figure 3 contains the locations of these temperature probes.

An HP-3497A data acquisition system, linked to a HP-9826A computer, was used to collect the voltage readings from all the measurement devices. The data collection and reduction program "DRPML", listed in Appendix C, allowed for the processing and storage of all the data by the HP-9826A computer.

Swensen [Ref. 17] provides calibration data for the pressure transducer, thermocouples, quartz thermometer and flowmeter.

C. TUBES TESTED

Eight enhanced tubes were manufactured for this thesis. Tests were also conducted on tubes studied by previous researchers to ensure repeatability of results. Table I contains a listing of all the tubes tested and additional tubes used in the comparison of results. All of the tubes assembled for this study were made from a single titanium MHT Korodense tube manufactured by Wolverine. Seven of the tubes were then wrapped with wire having diameters ranging from 0.1 to 1.6 mm to test enhancement effects. To attach the wire to the tubes, two different methods were used. The larger diameter (stiffer) wires ($\geq$ 0.5 mm) were wrapped around a rod

of a smaller diameter than the tube, this formed the wire into a tight coil. The wire was then fed onto the tube by twisting the coil and advancing it along the groove of the tube. The wire was then spot welded in place at each end of the active condensing surface. For the wires < 0.5 mm, one end was spot welded to the tube at the edge of the active surface. The wire was then tightly wrapped around the tube, by hand, in the groove and spot welded to the other end of the active surface. Both methods resulted in a constant wire pitch equal to the corrugation pitch of the tube. The wire was not physically attached to the active tube surface and did not act as a fin. The additional tubes included in Table I were manufactured for research conducted by O'Keefe [Ref. 18] and Mitrou [Ref. 14].

Table I. LISTING OF TUBES TESTED

Tube No.	Tube Type	Wire Diameter (mm)	Wire Spacing (mm)	Wire Pitch (mm)	P_w/D_w Ratio	Fractional[2] Coverage	Outside Diameter (mm)	Inside Diameter (mm)	Tube Material
M	MHT	None	None	None	None	0	16.07	13.53	Titanium
MW16	MHT	1.6	6.40	8.00	8.00	0.200	16.07	13.53	Titanium
MW10	MHT	1.0	7.00	8.00	8.00	0.125	16.07	13.53	Titanium
MW05	MHT	0.5	7.50	8.00	16.00	0.063	16.07	13.53	Titanium
MW04	MHT	0.4	7.60	8.00	20.00	0.051	16.07	13.53	Titanium
MW03	MHT	0.3	7.70	8.00	26.67	0.038	16.07	13.53	Titanium
MW02	MHT	0.2	7.80	8.00	40.00	0.025	16.07	13.53	Titanium
MW01	MHT	0.1	7.90	8.00	80.00	0.013	16.07	13.53	Titanium
L	LPD	None	None	None	None	0	15.85	13.47	Titanium
LW05	LPD	0.5	6.50	7.00	14.00	0.074	15.85	13.47	Titanium
ST0	Smooth	None	None	None	None	0	15.85	13.86	Titanium
ST1	Smooth	0.5	7.60	8.10	16.80	0.062	15.85	13.86	Titanium
ST2	Smooth	0.5	3.46	3.96	7.92	0.120	15.85	13.86	Titanium
SC1	Smooth	0.5	3.13	3.63	7.26	0.141	19.05	12.71	Copper

[2]Fractional coverage in this thesis is the ratio of the product of the wire diameter and the wire length on the active surface to the total active surface area.

IV. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

A. TUBE PREPARATION

To ensure consistent results in data collection, a continuous film of condensate must be present over the entire tube surface. A chemical treatment procedure used by Guttendorf [Ref. 16] and several other researchers at NPS was used to produce filmwise condensation on the tube surface. Prior to installation into the test section, the tube was chemically treated as follows:

1. The inside and outside of the tube were thoroughly cleaned with mild soap using a soft bristle brush. The soap was rinsed off with distilled water, then the tube was rinsed with acetone. Distilled water was again poured over the tube, to ensure the water formed a continuous film on the tube surface. If breaks in the film were observed (an indication of impurities on the tube surface) the cleaning process was repeated. Once a continuous film was present, the active surface was not handled, thus minimizing the possibility of contamination.

2. The tube was then placed in a steam bath.

3. A solution of 50% by weight sodium hydroxide and ethyl alcohol was mixed for treating the tube surface. The solution was kept warm to ensure a watery consistency.

4. The solution was then applied over the tube surface, with a small brush, in 10 minute intervals for one hour. While applying the solution, the tube was rotated so the entire surface could be treated. If the tube was treated previously, the solution was only applied every 5 minutes over a 20 minute period.

5. After the tube surface was treated, it was removed from the steam bath and rinsed with distilled water to remove any excess alcohol/sodium hydroxide solution. To verify

a continuous film will be produced in the presence of steam, the tube was returned to the steam bath, to ensure the entire surface wets easily.

6. Without touching the active surface, the tube was removed from the steam bath and immediately mounted in the test section of the boiler apparatus. If tests were to be conducted with an insert, the insert was installed prior to securing the coolant flow piping to the test section.

The oxide layer formed by the chemical treatment promotes a continuous film on the tube surface. Due to the negligible thickness of the oxide film, its thermal resistance was considered insignificant compared to the overall thermal resistance of the tube.

B. SYSTEM START-UP AND SHUTDOWN PROCEDURES

After the tube has been installed in the test section, the system can be brought on-line using the following procedures:

1. The boiler section must be filled with distilled water to a level approximately 4 to 6 inches above the top of the heater elements. The boiler can be filled by attaching a hose from the distilled water tank to the piping at the boiler drain/fill valve. Opening the vent valve on the auxiliary condenser allows for gravity filling of the boiler. To drain the boiler, disconnect the distilled water tank hose and attach the hose leading to the drain in bilge area below the boiler. Then open the drain/fill valve and allow the water to gravity drain from the boiler.

2. When the appropriate water level has been achieved, shut both the fill/drain valve and the vent valve on the auxiliary condenser.

3. Energize the data acquisition system, computer, printer, and quartz thermometer power supply. Load the software program DRPML and check for proper operation. Then verify that the thermocouple outputs all correspond to the same ambient temperature.

4. Open the fill valve to the cooling water sump and adjust the flow rate to ensure the drain box does not overflow. The fill valve for the sump is located to the left of the boiler switchboard.

5. Perform a leak test on the cooling water systems.

   a. Energize the cooling water supply pumps and adjust the rotameter flow rate from 20% to 80% while checking for leaks in the test section. Then secure the control valve and de-energize the cooling water supply pumps.

   b. Open the control valve for the auxiliary condenser and adjust the flow rate to at least 30% and check for leaks in the system. After completing the leak check, reset the flow rate to the auxiliary condenser to the desired position, minimum of 10%.

6. Place the system under a vacuum. To do this, shut the drain valve in the plexiglass cold trap and energize the vacuum pump. Check the pressure gage on the vacuum pump to ensure proper operation and open the suction valve located on the side of the auxiliary condenser. After the vacuum pump has reduced the system pressure to below 3 psia, shut the suction valve and secure the vacuum pump.

7. With the system under a vacuum, the heaters may be energized . Three switches must be placed in the "ON" position to energize the heaters.

   a. Switch #3 on panel p5, in the main hallway adjacent to room H-106.

   b. The heater load bank circuit breaker on the left side of the boiler heater switchboard.

   c. The condensing rig boiler power switch, on the front of the boiler heater switchboard.

   When the heaters are energized, the power level should be adjusted to 50 Volts, using the silicon control rectifier on the boiler control switchboard. If the system is below 2 psia, the power level should initially set to 40 Volts to minimize vibrational shock to the system caused from vapor bubble formation and collapse. As the system warms up, the power can be increased, in increments of 10 Volts, until the desired setting is reached.

8. After the system pressure rises above 4 psia, non-condensible gases need to be purged from the system. This can be accomplished by following the procedures outlined in step 6. Throughout the purging procedure, the horizontal tube coolant flow should remain secured, while the flow rate to the auxiliary condenser can be adjusted until all the gases have been evacuated. When the auxiliary condenser is warm to the touch everywhere, and condensate has formed in the plexiglass container, most of the non-condensible gases have been removed. The initial purging of the system may take between 15 and 30 minutes. This process should be repeated every few hours during extended operation.

9. To establish filmwise condensation on the tube being tested, the following steps should be performed:

   a. Allow the system vapor temperature to increase to ≈90 °C (at least 3800 microvolts on channel 40).

   b. Increase the flow rate in the auxiliary condenser to 50% or 60% and allow the vapor temperature to reduce to ≈75 °C (approximately 3200 microvolts).

   c. Secure coolant flow to the auxiliary condenser and allow the vapor temperature to increase to about 85 °C (≈3700 microvolts). This forms a steam blanket over the tube.

   d. Initiate coolant flow of 80% in the single horizontal tube.

   e. Adjust the auxiliary condenser flow rate to maintain the desired temperature and pressure for data collection.

   If, after performing steps 9 a. through 9 e., some dropwise condensation persists, repeat step 9 again. If dropwise condensation continues, the tube should be removed, cleaned and retreated in accordance with the procedures listed in section IV. A. A cutout section in the insulation above the test section allows for a light to be shown on the upper surface of the tube in order to check for a continuous film on the tube surface.

10. Run the software program DRPML by pressing the "RUN" key on the keyboard. The program will prompt you with questions for the necessary information required to run as listed by O'Keefe [Ref. 18] and in Appendix C.

11. Ensure the system has been operating at steady-state conditions for at least 30 minutes prior to continuing past the question "Enter the flowmeter reading".

12. Vacuum runs are conducted at a heater setting of 90 Volts and 1980 ± 10 microvolts on channel 40. This corresponds to T_{Sat} ≈48°C, and a vapor velocity of ≈ 2 m/s.

13. The atmospheric runs are conducted at a heater setting of 175 Volts and 4280 ± 10 microvolts on channel 40. This corresponds to T_{Sat} ≈100°C, and a vapor velocity of ≈1 m/s. Special care must be used when operating at atmospheric pressure to ensure over-pressurization and rupture does not occur.

14. When taking readings, double check the flowmeter reading prior to accepting any data point. If both vacuum and atmospheric pressure runs are to be conducted in the same day, the vacuum data should be collected first. This eliminates the long cool down time required after an atmospheric pressure run.

After data has been collected, the system should be secured utilizing the following procedures:

1. Secure power to the heating elements. Turn off the switches in the reverse order listed in step 7 of the start-up procedures.

2. Secure coolant flow to the auxiliary condenser. If the system is to remain at vacuum pressure until the next data run, then the auxiliary condenser can be used in assisting to cool the system down, provided the same tube will be used for the following test.

3. Secure the coolant flow through the single horizontal tube by securing the coolant pumps.

4. Secure the water flow to the coolant sump tank.

5. To return the system to atmospheric pressure, slowly open the vent valve on the auxiliary condenser. To avoid contaminating the system, keep any foreign material away from the vicinity of the vent valve during this procedure.

6. If an emergency should arise, such as an over-pressurization or breakage, ensure the heater power

is secured first. Then, let the system cool down prior to checking for damage.

C. DATA COLLECTION PROCEDURE

After the tube has been installed and the system has been operating for a minimum of 30 minutes, data collection may begin. Each run consisted of data points taken at coolant flow rate settings from 80% to 20% and back up to 80%, in 10% increments. This allowed for each data point to be checked for repeatability during the run. Before a data point was accepted, sample readings were taken to ensure the coolant temperature difference, the overall heat transferred, and the saturation temperature were stable. The temperature difference between the inlet and outlet coolant flow must be stabilized ($\pm 0.01\ ^{\circ}C$) prior to recording data. After setting the coolant flow rate, the aforementioned parameters required between 5 and 15 minutes to stabilize.

D. DATA REDUCTION PROCEDURE

For a slice of the condenser tube, the overall thermal resistance from vapor to coolant can be represented by the sum of the coolant side resistance (R_i), the fouling resistance (R_f), the wall resistance (R_w), and the vapor side resistance (R_o), as shown in equation (4.1).

$$R_{total} = R_i + R_f + R_w + R_o \qquad (4.1)$$

Only clean tubes were tested so the fouling resistance was set to zero, therefore:

$$R_{total} = R_i + R_w + R_o \tag{4.2}$$

Being convective in nature, the vapor and coolant side resistances can be expressed as follows:

$$R_o = \frac{1}{h_o A_o} \tag{4.3}$$

$$R_i = \frac{1}{h_i A_i} \tag{4.4}$$

The wall resistance term comes from the general radial conduction equation for a concentric cylinder:

$$R_w = \frac{\ln(D_o/D_i)}{2\pi L k_m} \tag{4.5}$$

The total thermal resistance can be expressed in terms of the overall heat transfer coefficient (U_o) and the effective outside condensing area (A_o), as follows:

$$R_{total} = \frac{1}{U_o A_o} \tag{4.6}$$

The effective outside condensing area of the tube can be calculated using the following equation:

$$A_o = \pi D_o L \tag{4.7}$$

For the inside effective area, two different conditions are present. The area corresponding to the outside effective area, where heat transfer takes place radially, and the inlet

and outlet portions of the tube, where heat removal occurs axially. To account for this 'fin' effect, the extended fin assumption and associated fin efficiencies were used in the following expression:

$$A_i = \pi D_i (L + L_1\eta_1 + L_2\eta_2) \tag{4.8}$$

Substituting equations (4.3), (4.4), and (4.6) into equation (4.2) yields the following:

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + R_w + \frac{1}{h_o A_o} \tag{4.9}$$

From the data collected, the total heat transfer rate across the tube can be calculated directly from an energy balance using the coolant mass flow rate and the coolant temperature difference (from inlet to outlet) through the tube:

$$\dot{Q} = \dot{m} c_p (T_2 - T_1) \tag{4.10}$$

The total heat transfer rate can also be expressed in terms of the overall heat transfer coefficient, the effective outside condensing area, and the log mean temperature difference (LMTD):

$$\dot{Q} = U_o A_o (LMTD) \tag{4.11}$$

where:

$$LMTD = \frac{(T_2 - T_1)}{\ln\left[\frac{T_{sat} - T_1}{T_{sat} - T_2}\right]} \tag{4.12}$$

The measurements for LMTD were obtained in the following manner:

- T_1 was measured from a quartz thermometer installed at the inlet section of the coolant flow for the condenser tube.
- T_2 was measured with a quartz thermometer inserted downstream of the mixing chamber at the outlet section of the coolant flow for the condenser tube. A correction factor was applied to T_2 in order to compensate for viscous heating of the coolant through the tube. The corrections, which depend on the inside geometry of the tube, the coolant flow velocity, and the type of insert, are listed in Appendix A.
- T_{sat} was measured using the vapor thermocouple (channel 40).

Substituting equation (4.10) into equation (4.11) provides determination of the overall heat transfer coefficient directly from experimental measurements:

$$U_o = \frac{\dot{m} c_p (T_2 - T_1)}{A_o (LMTD)} \qquad \textbf{(4.13)}$$

With A_o, A_i, R_w, and U_o all known quantities, the only remaining unknowns in equation (4.9) are h_o and h_i, the outside and inside heat transfer coefficients. The modified Wilson plot technique was used to calculate these coefficients.

E. MODIFIED WILSON PLOT TECHNIQUE

In 1915, Wilson [Ref. 63], developed a method for indirectly determining the inside and outside thermal

resistance from an overall resistance. Wilson's method requires the heat flux of the system to remain constant. While this application proves valid in theory, difficulties arise when trying to maintain a constant heat flux while varying the cooling water velocity, Marto [Ref. 64].

Khartabil et al. [Ref. 65] provide a comprehensive listing of modifications to the original technique developed by Wilson. For a detailed development of the modified Wilson plot technique, the reader is referred to Marto [Ref. 64] and Marto and Nunn [Ref. 66].

Using the modified Wilson plot method to determine the inside and outside heat transfer coefficients requires one to choose a general form for each correlation. The program DRPML enables the user to select from several options. The inside heat transfer coefficient correlation can be written in simplified form as follows:

$$h_i = C_i \Omega \tag{4.14}$$

where Ω varies with the particular correlation used. Using the Sieder-Tate correlation [Ref. 49] (equation (2.19)):

$$\Omega = \frac{k_c}{D_i} Re^x Pr^{1/3} (\mu_c/\mu_w)^{0.14} \tag{4.15}$$

where the program allows the Reynolds number exponent (x) to be varied. Using the Sleicher-Rouse correlation [Ref. 50] (equation (2.21)):

$$\Omega = \frac{k_c}{D_i}(5 + 0.015\ Re_f^{\ c}\ Pr_w^{\ d}) \qquad \textbf{(4.16)}$$

where c and d are defined in equation (2.22) and (2.23) respectively. Using the Petukhov-Popov correlation [Ref. 51] (equation (2.24)):

$$\Omega = \frac{k_c}{D_i}\left[\frac{(\varepsilon/8)\ Re\ Pr}{K_1 + K_2(\varepsilon/8)^{1/2}\ (Pr^{2/3}-1)}\right] \qquad \textbf{(4.17)}$$

where ϵ, K_1, and K_2 are defined in equation (2.25), (2.26), and (2.27) respectively.

Similarly, the outside heat transfer coefficient correlation may be written in simplified form:

$$h_o = \alpha\ Z \qquad \textbf{(4.18)}$$

where Z can be selected from equation (2.1) (Nusselt's theory [Ref. 23]):

$$Z = \left[\frac{k_f^{\ 3}\ g\ \rho_f^{\ 2}\ h_{fg}}{\mu_f\ D_o\ (T_{sat}-T_{wo})}\right]^{1/4} \qquad \textbf{(4.19)}$$

or from equation (2.62) (Fujii's correlation [Ref. 29]):

$$Z = \frac{k_f}{D_o}\ F^{1/5}\ Re_{2\phi}^{\ 1/2} \qquad \textbf{(4.20)}$$

F and $Re_{2\phi}$ are defined in equation (2.4) and (2.5) respectively.

Substituting equation (4.14) and (4.18) into equation (4.9) yields:

$$\frac{1}{U_o A_o} = \frac{1}{C_i \Omega A_i} + R_w + \frac{1}{\alpha Z A_o} \qquad (4.21)$$

which can be written as:

$$\left[\frac{1}{U_o} - R_w A_o\right] \cdot Z = \frac{1}{C_i} \cdot \left[\frac{A_o Z}{\Omega A_i}\right] + \frac{1}{\alpha} \qquad (4.22)$$

By letting:

$$Y = \left[\frac{1}{U_o} - R_w A_o\right] \cdot Z \qquad (4.23)$$

$$X = \frac{A_o Z}{A_i \Omega} \qquad (4.24)$$

$$m_1 = \frac{1}{C_i} \qquad (4.25)$$

and:

$$b = \frac{1}{\alpha} \qquad (4.26)$$

Equation (4.22) can be written in simple linear form as:

$$Y = m_1 X + b \qquad (4.27)$$

Due to the temperature dependence of the parameters Ω and Z, the program utilizes an iterative procedure in the solution for each data point. A least-squares fit of equation (4.27) then determines C_i and α. To calculate h_o, the known value of

α can be used directly in equation (4.18); alternatively, with the known value of C_i, h_i can be calculated from equation (4.14), and applied to equation (4.9) in the following form:

$$h_o = \left[\frac{1}{U_o} - \left(\frac{A_o}{h_i A_i} + R_w A_o\right)\right]^{-1} \qquad (4.28)$$

F. ENHANCEMENT RATIO

The enhancement ratios in this thesis are used to express a comparison of enhanced tube results to smooth tube results, or to compare wire-wrapped corrugated tube results to plain corrugated tube results.

From Nusselt's theory, heat flux can be written as:

$$q = a\ (T_{sat} - T_{wo})^{3/4} \qquad (4.29)$$

where:

$$a = \alpha\left[\frac{k_f^3\ g\ \rho_f^2\ h_{fg}}{\mu_f\ D_o}\right]^{1/4} \qquad (4.30)$$

Heat flux can also be represented by:

$$q = h_o\ (T_{sat} - T_{wo}) \qquad (4.31)$$

Equating equations (4.29) and (4.31) yields:

$$h_o = a\ (T_{sat}-T_{wo})^{-1/4} \qquad (4.32)$$

Taking the ratio of the outside heat transfer coefficient from an enhanced tube, (h_{oe}), to a smooth tube (h_{os}), for the same (T_{sat}-T_{wo}) yields:

$$\epsilon_T = \frac{h_{oe}}{h_{os}} = \frac{a_e}{a_s} = \frac{\alpha_e}{\alpha_s} \qquad (4.33)$$

Similarly, the enhancement ratio for a wire-wrapped corrugated tube to a plain corrugated tube at the same (T_{sat}-T_{wo}) can be represented by:

$$\epsilon_{Tc} = \frac{h_{owc}}{h_{oc}} = \frac{a_{wc}}{a_c} = \frac{\alpha_{wc}}{\alpha_c} \qquad (4.34)$$

where the subscripts wc and c refer to wire-wrapped corrugated and plain corrugated tubes respectively.

For the purpose of this study all enhancement results for wire-wrapped corrugated tubes are based on ϵ_{Tc} and wire-wrapped smooth tube enhancements are based on ϵ_T.

V. RESULTS AND DISCUSSION

A. HEAT TRANSFER CORRELATIONS

Lorenz et al. [Ref. 52] conducted a thorough investigation of several inside heat transfer correlations to determine which correlation most accurately predicted their data for turbulent flow of water in smooth tubes. Their findings showed that the Petukov-Popov and Sleicher-Rouse correlations (equations (2.24) and (2.21) respectively) were the most accurate in predicting the inside heat transfer coefficient over the range of Prandtl numbers from 6.0 to 11.6. Consequently, O'Keefe [Ref. 18] made a comparison of his results obtained using both correlations to process data, which was collected from the same experimental apparatus used in this study. His results showed good agreement between the outside coefficients obtained for smooth copper and smooth titanium tubes, when the two correlations were used with the modified Wilson plot data reduction technique. Based on his findings, O'Keefe [Ref. 18] processed most of his data using the Petukhov-Popov correlation. All data collected in this study were processed using the Petukov-Popov correlation so a direct comparison could be made with the results obtained by O'Keefe [Ref. 18].

The data collection and reduction program, DRPML, listed in Appendix C, allows for the selection from two possible outside heat transfer correlations, the Nusselt theory or the Fujii correlation (equations (2.1) and (2.6) respectively). Figure 5 shows the reduced results for h_o obtained from using these two equations for a vacuum pressure run on a plain MHT Korodense tube. It can be seen that there is good agreement between the two equations. This indicates that the leading coefficient, α, obtained from the modified Wilson plot method using the Nusselt theory compensates for any vapor velocity effect inherent in the Fujii correlation. O'Keefe [Ref. 18] processed all of his data using the Nusselt correlation; so for comparison purposes, all further calculations of the outside heat transfer coefficient in the present work have also been made using the Nusselt theory.

B. VERIFICATION AND REPEATABILITY OF RESULTS

Several runs were made using the same tubes tested by previous researchers to verify system operation and data collection procedures. The five tubes that were tested included two smooth titanium tubes and two LPD Korodense titanium tubes tested by O'Keefe [Ref. 18]; of these, one of each was wrapped with a 0.5 mm diameter titanium wire. The fifth tube was a smooth copper tube wrapped with a 0.5 mm diameter titanium wire from Mitrou's work [Ref. 14]. Figures 6 and 7 are comparisons of the outside heat transfer

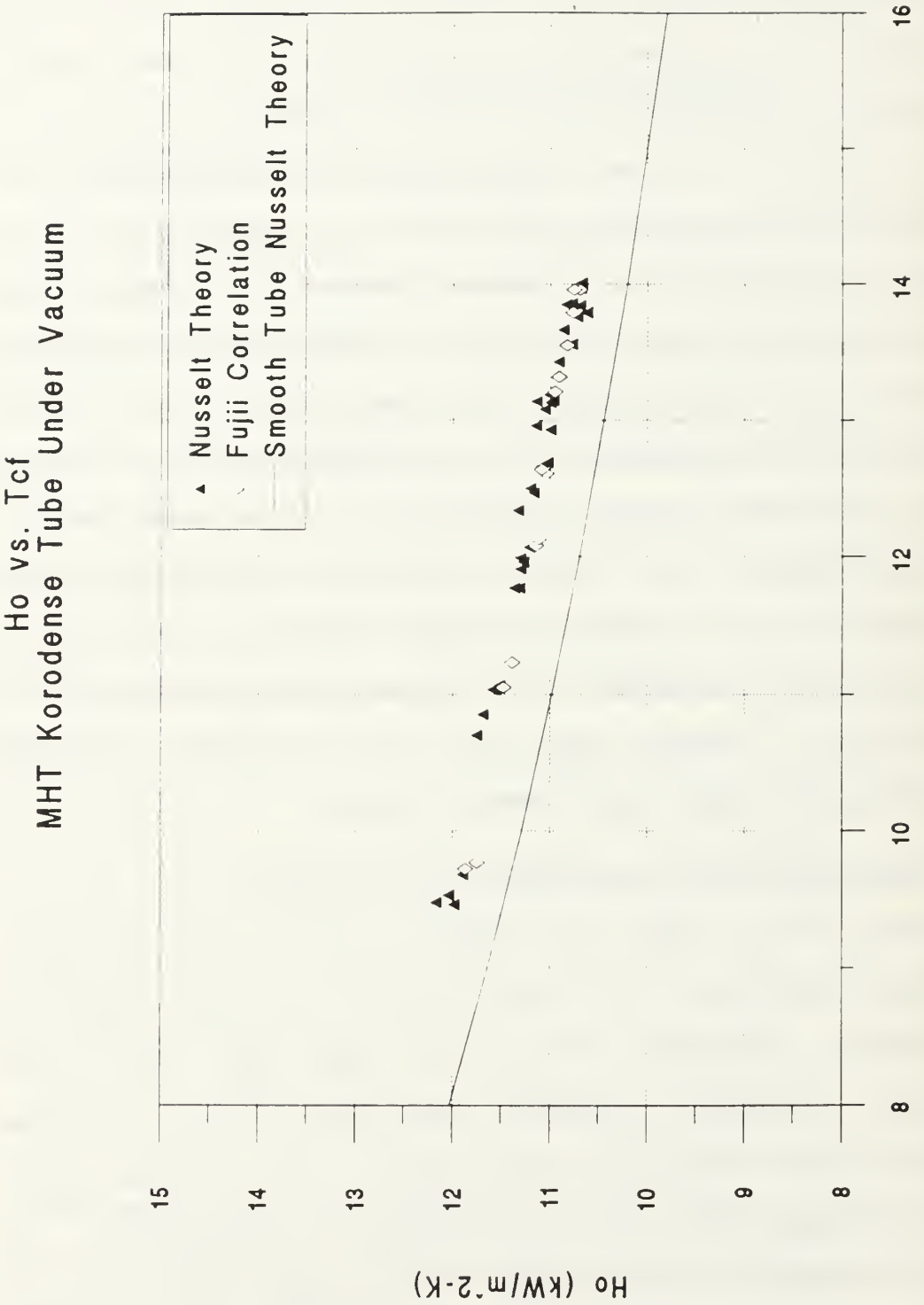

Figure 5. h_o vs. ΔT_{cf} for a Plain MHT Korodense Tube Under Vacuum

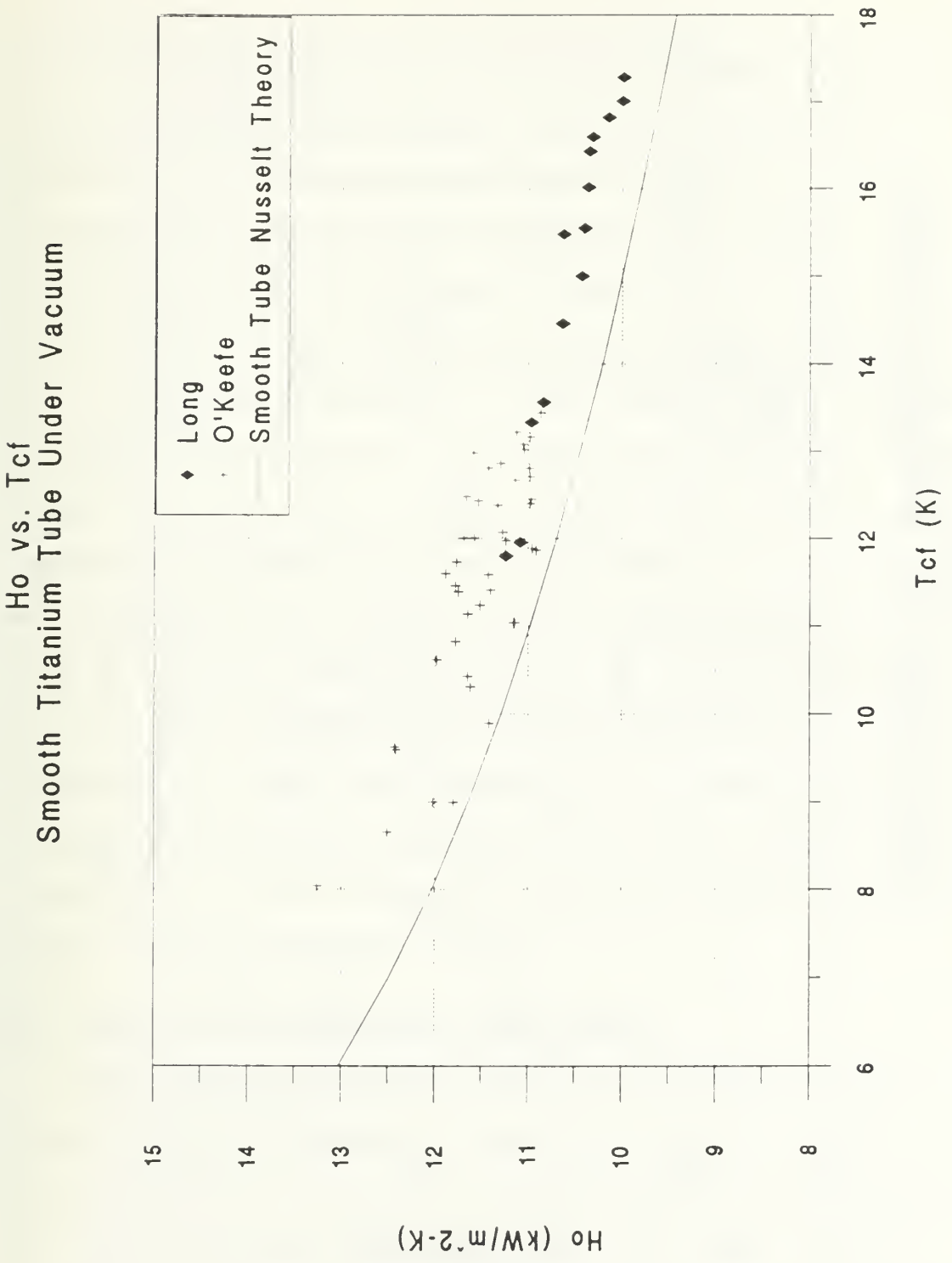

Figure 6. h_o vs. ΔT_{cf} for a Smooth Titanium Tube Under Vacuum

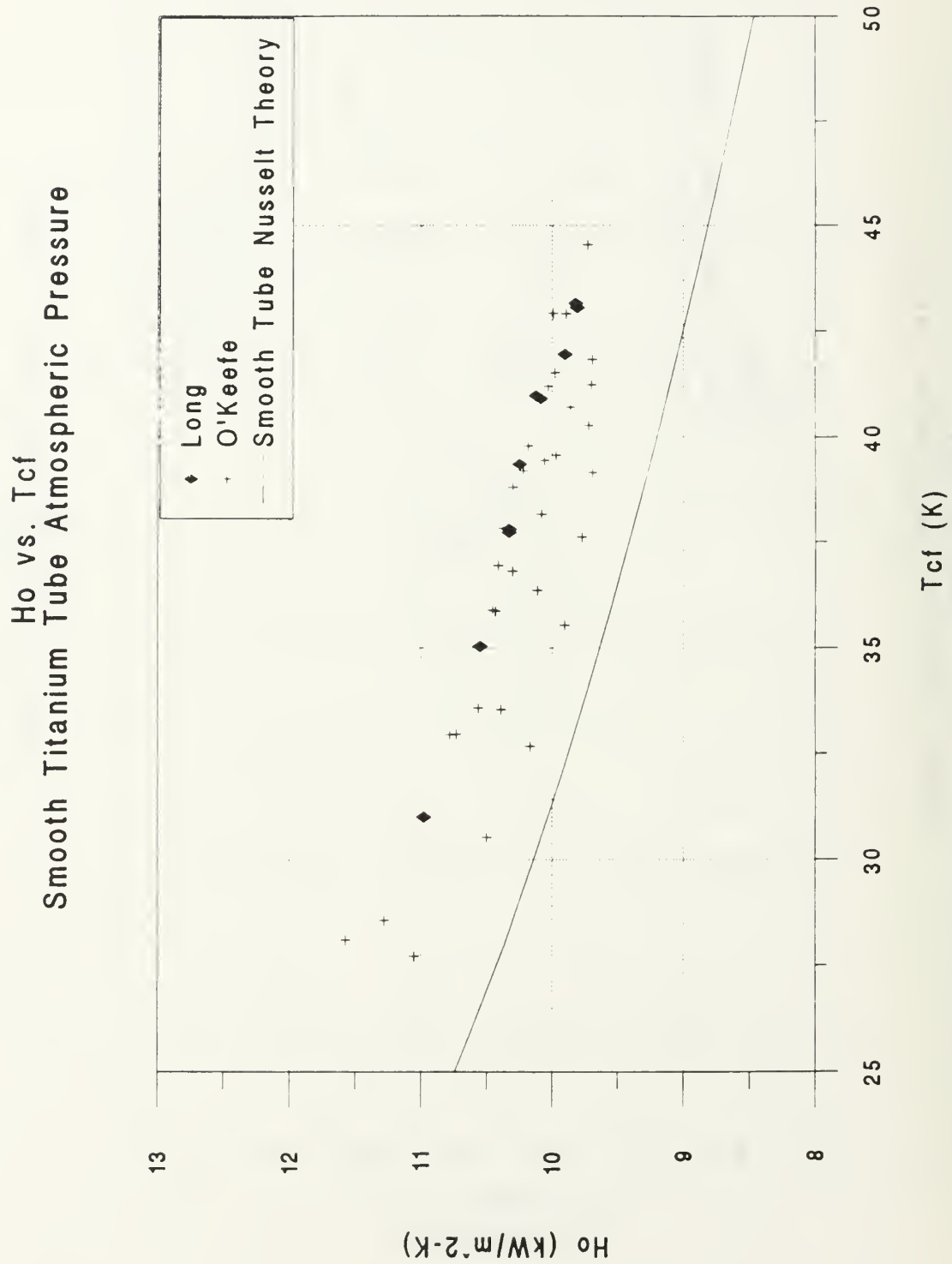

Figure 7. h_o vs. ΔT_{cf} for a Smooth Titanium Tube at Atmospheric Pressure

coefficient for a vacuum and an atmospheric pressure run respectively for data collected in this study and the study conducted by O'Keefe [Ref. 18] for the smooth titanium tube. The figures show good agreement for the two sets of data. The separation in the data sets seen in Figure 6 is due to a higher coolant water inlet temperature when O'Keefe conducted his runs. Tables II through VII contain a listing of all the data collected by O'Keefe, Mitrou and from the present study for comparison purposes in this study. The researcher initials are as follows: (O)=O'Keefe [Ref. 18], (L)=Long, and (M)=Mitrou [Ref. 14]. The average variation for α, the leading coefficient for the outside heat transfer equation, was less than 3.3%, with 90% of the results differing by less than 2%. The C_i values obtained in this study differed by as much as 8.5% compared with values obtained by previous researchers. This larger difference is possibly due to the uncertainty as to which HEATEX insert was used in O'Keefe's experiments. Four different inserts were available and each had a slightly different length.

C. ANALYSIS OF CORRUGATED TUBE RESULTS

To establish a base line for the enhancement ratios of the wire-wrapped MHT Korodense tubes, an initial series of runs were conducted to determine the heat transfer characteristics of the plain MHT Korodense tube. The data obtained are presented in Table VIII. Figure 8 shows a near unity

Table II. SMOOTH TITANIUM TUBE AT ATMOSPHERIC PRESSURE

	HEATEX Insert	
Data Run/Researcher	C_i	α
FONMAHT1 (O)	2.38	0.75
FONMAHT2 (O)	2.38	0.77
FONMAHT3 (O)	2.39	0.76
FONMAHT4 (O)	2.41	0.75
FONMAHT5 (O)	2.20	0.77
FONMAHT6 (O)	2.54	0.76
FONMAHT7 (O)	2.51	0.75
LSNTHA1 (L)	2.90	0.75
	No Insert	
FONMANT1 (O)	1.21	0.75
FONMANT2 (O)	1.18	0.76
FONMANT3 (O)	1.17	0.77
FONMANT4 (O)	1.18	0.76
FONMANT5 (O)	1.24	0.79
LSNTNA1 (L)	1.17	0.82

enhancement of the outside heat transfer coefficient for the MHT Korodense tube (having a groove pitch of 8 mm) over smooth titanium tube results. This is consistent with the findings of Rabas [Ref. 41] where, in a comparison of an extensive collection of data on spirally indented tubes he found:

> ... that there is no appreciable enhancement for condensation on roped tubes for groove pitches greater than 4 mm.

Table III. SMOOTH TITANIUM TUBE AT VACUUM PRESSURE

Data Run/Researcher	C_i	α
	HEATEX Insert	
FONMVHT3 (O)	2.55	0.85
FONMVHT4 (O)	2.29	0.79
FONMVHT5 (O)	2.42	0.79
LSNTHV1 (L)	2.87	0.78
LSNTHV2 (L)	2.87	0.79
LSNTHV3 (L)	2.43	0.79
LSNTHV4 (L)	2.50	0.78
	No Insert	
FONMVNT2 (O)	1.08	0.82
FONMVNT3 (O)	1.08	0.79
FONMVNT4 (O)	1.07	0.85
FONMVNT5 (O)	1.11	0.82
LSNTNV1 (L)	1.13	0.83
LSNTNV2 (L)	1.13	0.84
LSNTNV4 (L)	1.11	0.83

A comparison of the C_i values for the no insert runs on the smooth tube (Tables II and III) and LPD tube (Table V) indicate increases in h_i from 73 to 74% for vacuum and atmospheric pressure runs respectively. As discussed earlier, Wolverine [Ref. 2] reported a 25% increase in the inside heat transfer coefficient for the MHT Korodense tube when compared to the LPD Korodense tube. Comparison of the C_i values for the no insert runs on the MHT tube (Table VIII) and the LPD tube

Table IV. 0.5 mm WIRE-WRAPPED SMOOTH TITANIUM TUBE WITH HEATEX INSERT

Data Run/Researcher	C_i	α
	Atmospheric Pressure	
FONMAH6T2 (O)	2.39	0.99
FONMAH5T3 (O)	2.37	1.01
LSW1THA1 (L)	2.67	1.04
	Vacuum Pressure	
FONMVH6T1 (O)	2.16	0.95
FONMVH6T2 (O)	2.21	0.95
LSW1THV1 (L)	2.59	0.94

(Table V) indicate increases in h_i comparable to those reported by Wolverine [Ref. 2], 21% for the atmospheric pressure runs and 25% for the vacuum runs. This indicates that as the groove depth increases from the smooth tube (zero) to the LPD tube value (≈0.33 mm) most of the increase in the inside heat transfer coefficient due to corrugation has already been realized. The additional groove depth of the MHT tube provides only a 21 to 25% further increase of the inside heat transfer above the LPD results (MHT tube groove depth ≈0.5mm), while the pressure drop doubles [Ref. 2].

Figures 9 and 10 show the effect of using the HEATEX insert on the overall heat transfer coefficient (U_0). The general trend for U_0 to increase with increasing coolant flow velocity is due to improved coolant mixing and a lower mean

Table V. PLAIN LPD KORODENSE TUBE

Data Run/Researcher	C_i	α
Atmospheric Pressure HEATEX Insert		
FONMAHLT2 (O)	2.90	0.90
FONMAHLT3 (O)	2.89	0.92
LLNTHA1 (L)	3.11	0.95
Atmospheric Pressure No Insert		
FONMANLT2 (O)	2.06	0.92
FONMANLT3 (O)	1.99	0.94
LLNTNA2 (L)	2.17	0.95
Vacuum Pressure HEATEX Insert		
FONMVHLT1 (O)	2.72	0.94
FONMVHLT2 (O)	2.67	0.95
LLNTHV2 (L)	3.02	0.97
Vacuum Pressure No Insert		
FONMVNLT2 (O)	1.87	0.95
FONMVNLT3 (O)	1.86	0.96
LLNTNV3 (L)	1.99	0.96

bulk fluid temperature. Increases range from 3% at a coolant flow rate of 3.83 m/s up to 9% at a flow rate of 1.02 m/s. This increase is attributed to the greater turbulence of the coolant flow due to the presence of the insert and can be seen in the higher C_i values for the HEATEX runs for every tube tested. A comparison of O'Keefe's data [Ref. 18] for smooth titanium and LPD Korodense titanium tubes, tested with and

Table VI. 0.5 mm WIRE-WRAPPED LPD KORODENSE TUBE WITH HEATEX INSERT

	Atmospheric Pressure	
Data Run/Researcher	C_i	α
FONMAHL3T3 (O)	2.84	0.97
LLW05THA1 (L)	3.03	0.98
LLW05THA2 (L)	3.06	0.98
	Vacuum Pressure	
FONMVHL3T1 (O)	2.61	0.99
LLW05THV1 (L)	2.78	0.98
LLW05THV2 (L)	2.78	0.98

without a HEATEX insert indicates a 20% increase in U_0 for the smooth tube and a 7.9% increase in U_0 for the LPD tube when tested at a coolant velocity of ≈2.5 m/s. For a coolant flow rate of ≈2.5 m/s the present study shows a 7.2% increase in U_0 for the MHT tube when a HEATEX insert is used. This trend indicates that a more severe corrugation groove depth (zero for the smooth tube, 0.33 mm for the LPD tube and 0.5 mm for the MHT tube) results in a smaller increase in U_0 with the addition of an insert. The grooves present in the MHT and LPD tubes cause greater turbulence in the coolant flow than the inside walls of the smooth tube. Therefore, the addition of an insert for a corrugated tube (which already has turbulent flow) has a less pronounced effect on U_0 compared to the effect realized for a smooth tube.

Table VII. 0.5 mm WIRE-WRAPPED SMOOTH COPPER TUBE WITH HEATEX INSERT

Data Run/Researcher	C_i	α
Atmospheric Pressure		
FONMAH71C1 (O)	3.07	1.50
LSW71CHA1 (L)	3.15	1.28
S71A305* (M)	2.69	1.50
S71A314* (M)	2.69	1.50
Vacuum Pressure		
FONMVH71C2 (O)	2.76	1.28
LSW71CHV1 (L)	2.94	1.23
S71V296* (M)	2.50	1.27

* Runs conducted with wire-wrapped insert

D. ANALYSIS OF WIRE-WRAPPED CORRUGATED TUBE RESULTS

Seven different titanium wire diameters ranging from 0.1 mm to 1.6 mm were used to wrap separate MHT Korodense tubes. Tests were conducted at atmospheric and vacuum conditions and the results were compared to the plain MHT Korodense tube data to determine the enhancement effects attributable to wire-wrapping. Wire-wrapped smooth tube data obtained by previous researchers were also used for comparison to establish if similar trends exist.

The enhancement due to wire-wrapping can be seen directly in Figure 11 where the averaged U_0 (averaged for all data runs at each flow rate) are plotted for all the wire diameters.

Table VIII. PLAIN MHT KORODENSE TUBE

Atmospheric Pressure HEATEX Insert		
Data Run	C_i	α
LMNTHA7	3.34	0.79
LMNTHA8	3.31	0.79
LMNTHA9	3.32	0.80
Atmospheric Pressure No Insert		
LMNTNA7	2.49	0.80
LMNTNA8	2.47	0.80
LMNTNA9	2.56	0.80
Vacuum Pressure HEATEX Insert		
LMNTHV7	3.07	0.78
LMNTHV8	3.01	0.79
LMNTHV9	3.06	0.78
Vacuum Pressure No Insert		
LMNTNV7	2.36	0.77
LMNTNV8	2.39	0.76
LMNTNV9	2.43	0.77

Here the 0.4 mm wire-wrap appears to give the best heat transfer with an enhancement of about 3%. Similar trends for the outside heat transfer coefficient can also be seen in Figures 12 and 13. The plain MHT Korodense tube results are included to show the relative enhancements for each size of wire. Figure 12 shows an increasing trend with decrease in wire diameter starting from the 1.6 mm wire-wrap (P_w/D_w=5) and

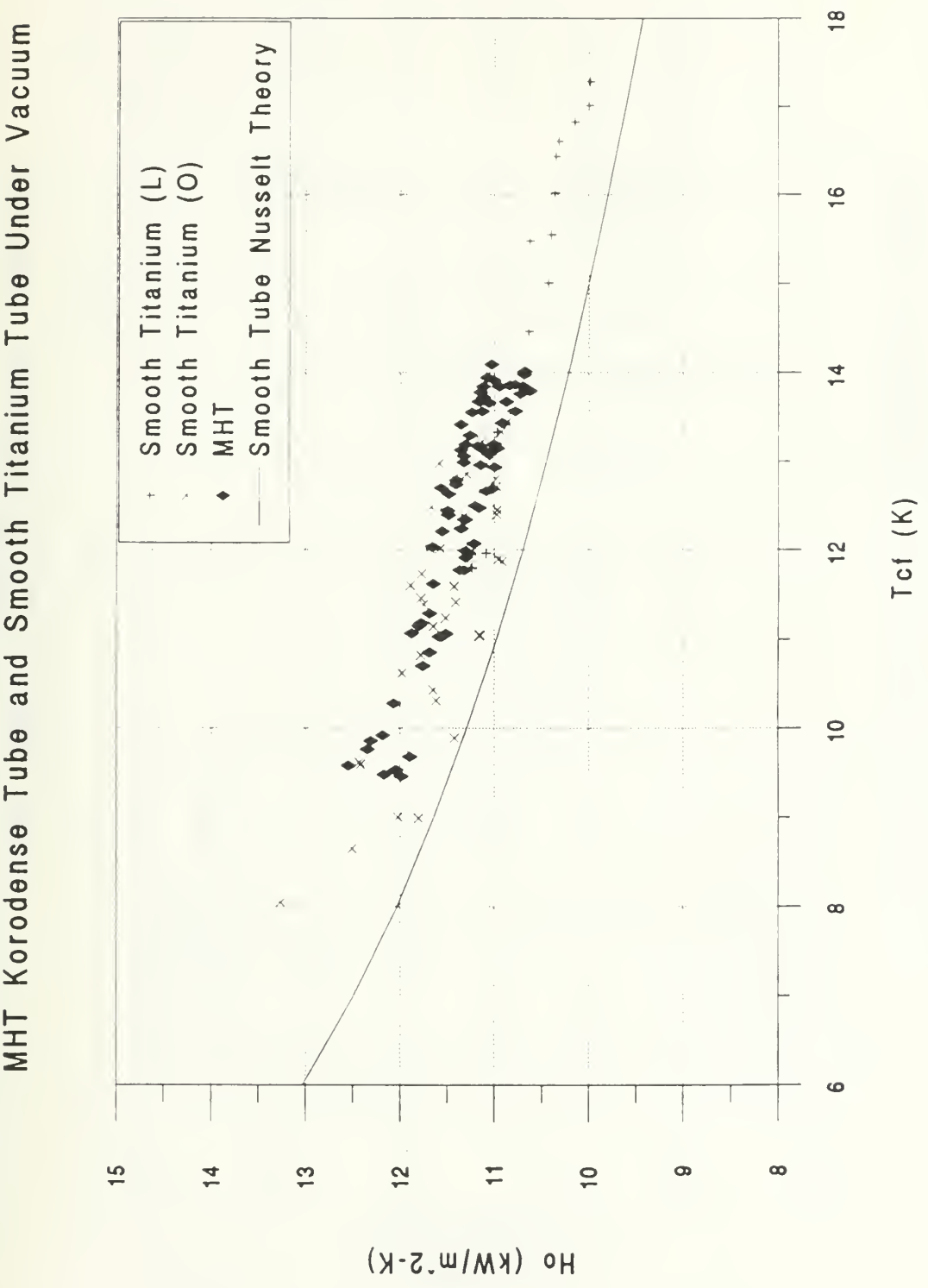

Figure 8. h_o vs. ΔT_{cf} for a Smooth Titanium and a Plain MHT Korodense Tubes Under Vacuum

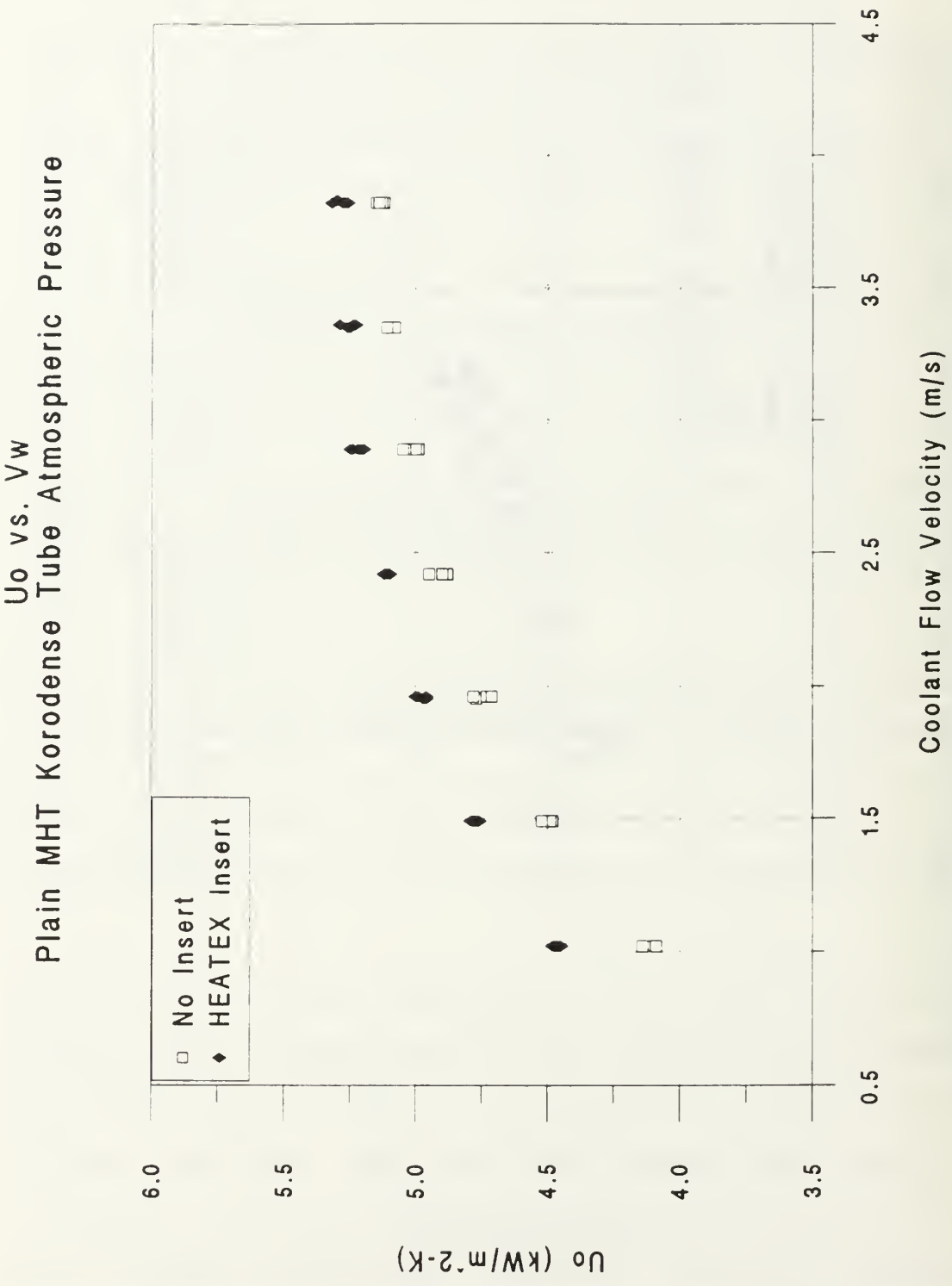

Figure 9. U_o vs. V_w for a Plain MHT Korodense Tube at Atmospheric Pressure

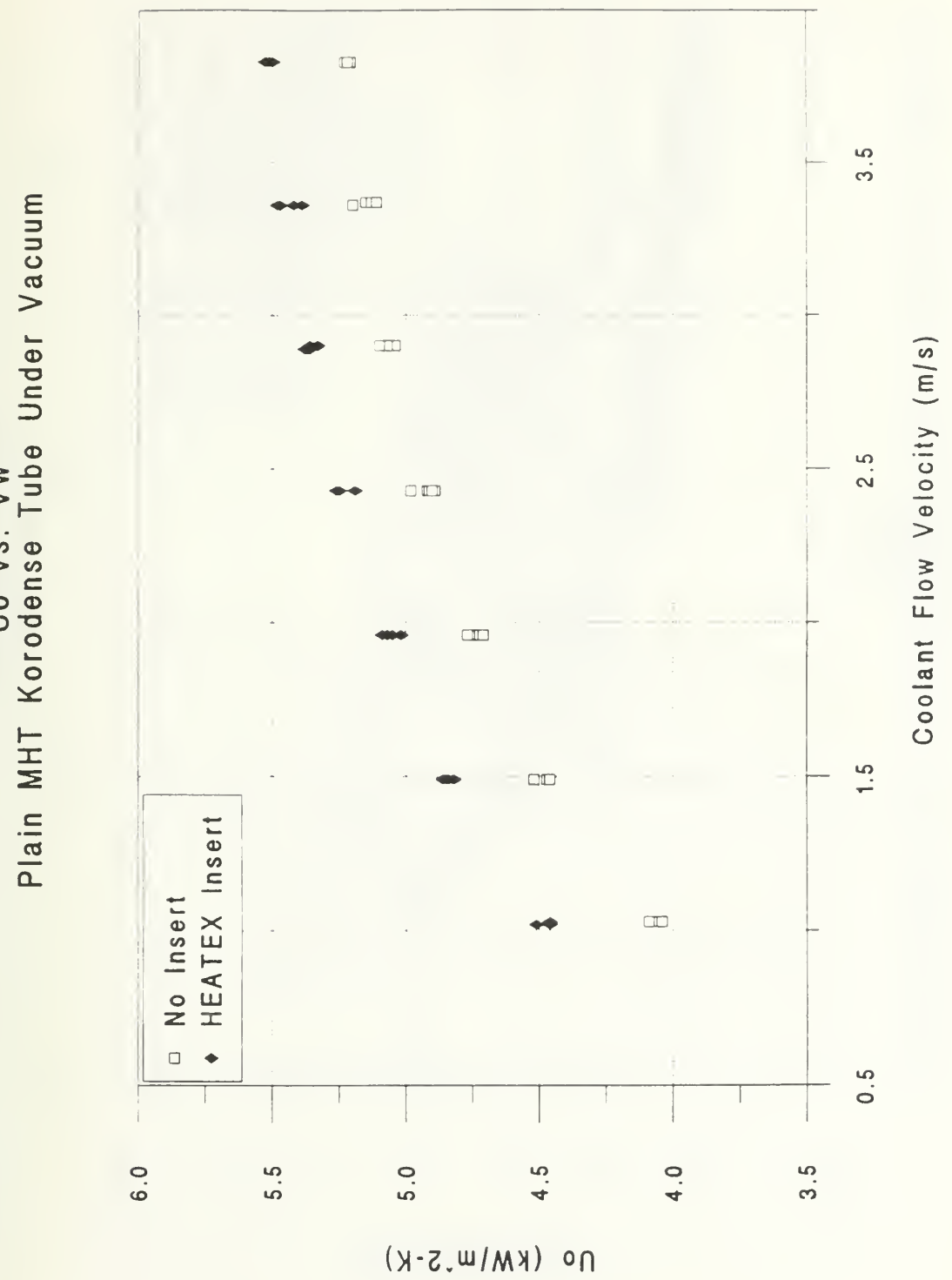

Figure 10. U_o vs. V_w for a Plain MHT Korodense Tube Under Vacuum

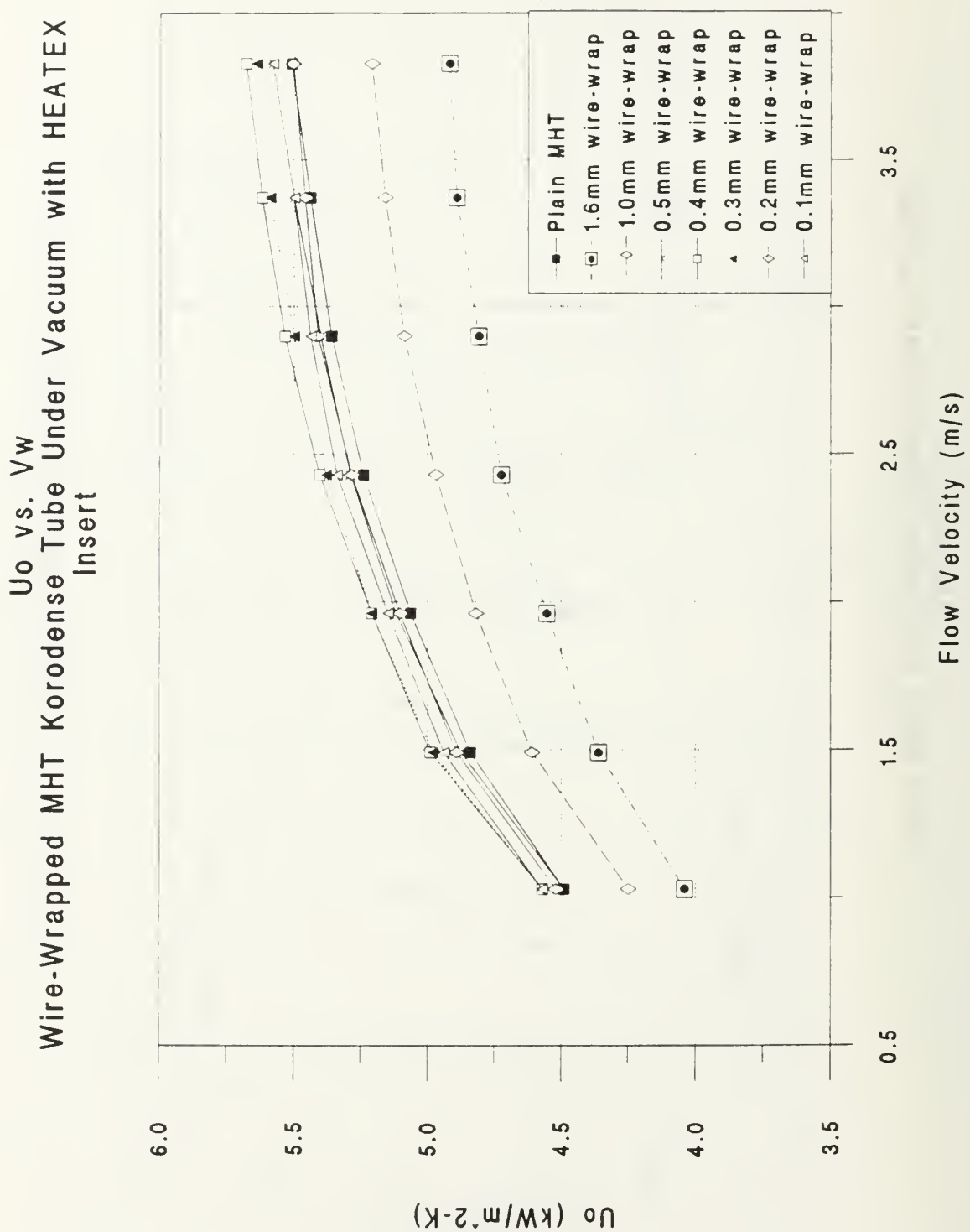

Figure 11. U_o vs. V_w for Wire-Wrapped MHT Korodense Tubes Under Vacuum with HEATEX Insert

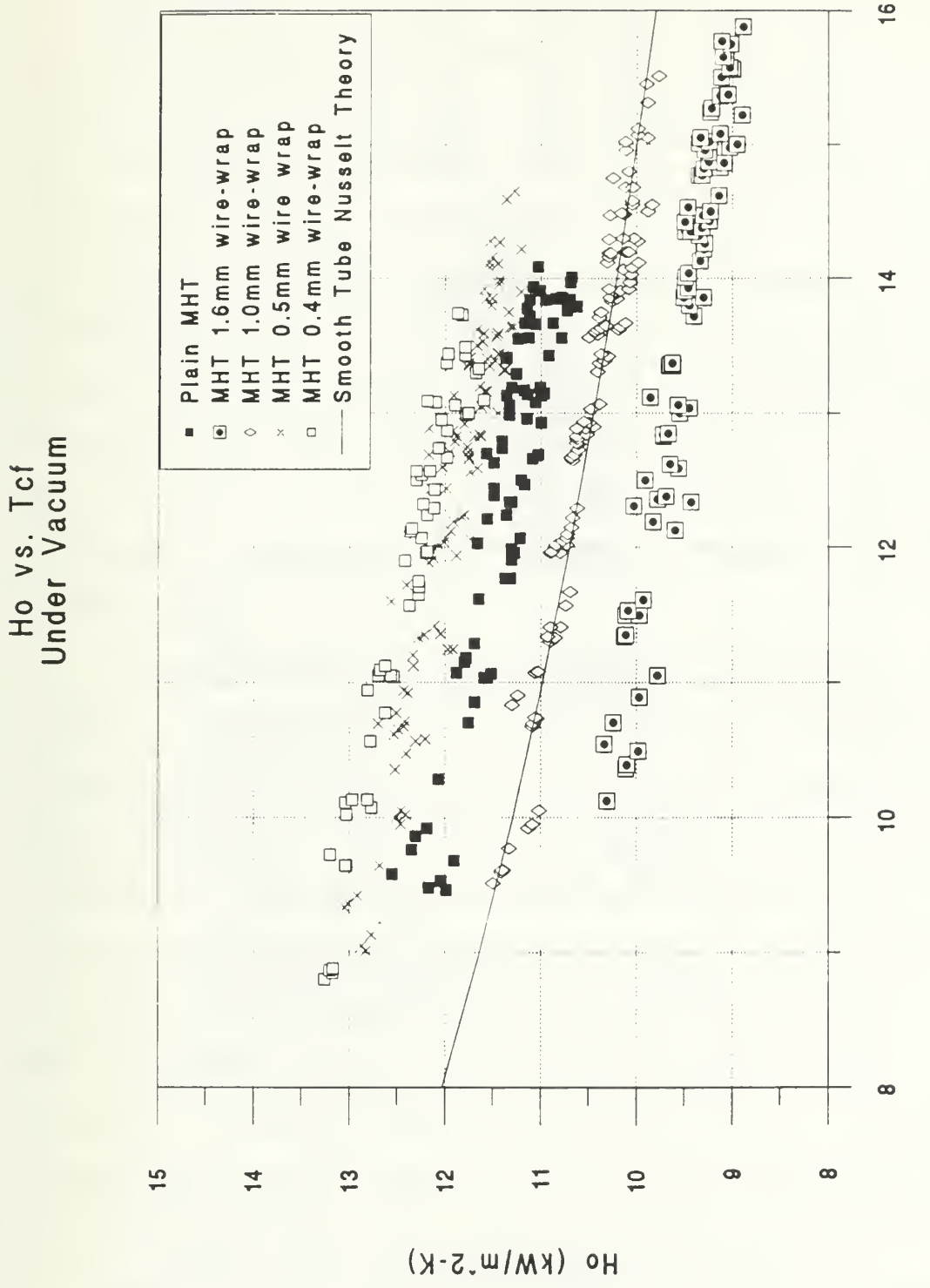

Figure 12. h_o vs. T_{cf} for Wire-Wrapped MHT Korodense Tubes Under Vacuum

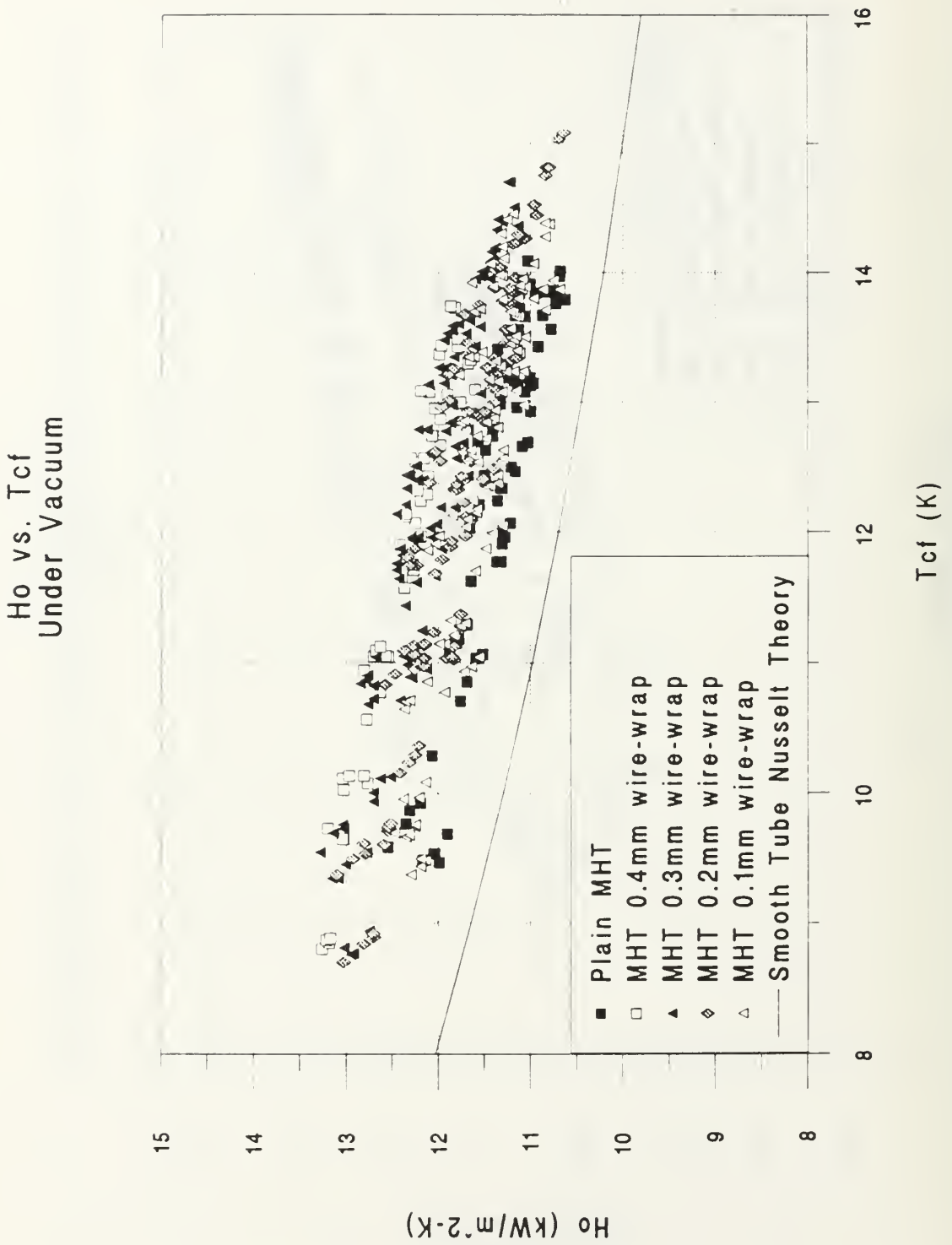

Figure 13. h_o vs. T_{cf} for Wire-Wrapped MHT Korodense Tubes Under Vacuum

an enhancement ratio of 0.88 to the 0.4 mm wire-wrap (P_w/D_w=20) with an enhancement ratio of 1.08. Figure 13 completes the data and shows the trend returning to the plain MHT tube results, starting with the 0.4 mm wire-wrap and ending with the 0.1 mm wire-wrap (P_w/D_w=80). Two separate figures were used to help eliminate the clutter from the overlapping data. Table IX contains the averaged C_i and α values for all the conditions tested (vacuum and atmospheric pressure, with and without the HEATEX insert) for the plain MHT tube and all the wire-wrapped MHT tubes. Two to four tests were conducted at each condition to ensure repeatability of the data.

The wire-wrapped MHT tube data were also checked to see if there was a relationship between the fractional coverage and the pitch to wire diameter ratio to the enhancement over the plain MHT tube (E_{Tc}). Figure 14 shows the relationship between the enhancement ratio and the pitch to wire diameter ratio and Figure 15 shows enhancement ratio versus fractional coverage. Data obtained by O'Keefe [Ref. 18] for wire-wrapped LPD Korodense tubes are also included in the figures. However, the number of his tests are limited to only 3 wire diameters (0.5mm, 1.0mm and 1.6mm). The data clearly indicate that wrapping with a large diameter wire causes a degradation in performance. As the wire diameter is decreased, the enhancement passes through a maximum of about 8%, corresponding to a $P_w/D_w \approx 20$ and a fractional coverage of ≈5%.

Table IX. WIRE-WRAPPED AND PLAIN MHT KORODENSE TUBES

Tube	Atmospheric Pressure			
	No Insert		Heatex Insert	
	C_j	α	C_j	α
Plain	2.51	0.82	3.32	0.79
1.6mm wire-wrap	2.31	0.72	2.92	0.73
1.0mm wire-wrap	2.35	0.78	3.27	0.79
0.5mm wire-wrap	2.50	0.85	3.19	0.85
1.0mm wire-wrap	2.53	0.84	3.38	0.85
0.3mm wire-wrap	2.52	0.84	3.27	0.85
1.0mm wire-wrap	2.53	0.82	3.38	0.82
0.4mm wire-wrap	2.50	0.81	3.36	0.82
	Vacuum Pressure			
Plain	2.99	0.77	3.05	0.79
1.6mm wire-wrap	2.17	0.67	2.84	0.69
1.0mm wire-wrap	2.20	0.82	2.99	0.73
0.5mm wire-wrap	2.84	0.82	3.05	0.81
0.4mm wire-wrap	2.31	0.83	3.03	0.84
0.3mm wire-wrap	2.31	0.82	3.14	0.73
0.2mm wire-wrap	2.39	0.81	3.16	0.80
0.1mm wire-wrap	2.42	0.78	3.23	0.80

As the wire diameter is further decreased, the enhancement ratio returns to unity, i.e. back to the plain tube performance. The results from O'Keefe [Ref. 18] for the LPD Korodense tube definitely show the same trends as the MHT tube, but the results are somewhat inconclusive due to lack of

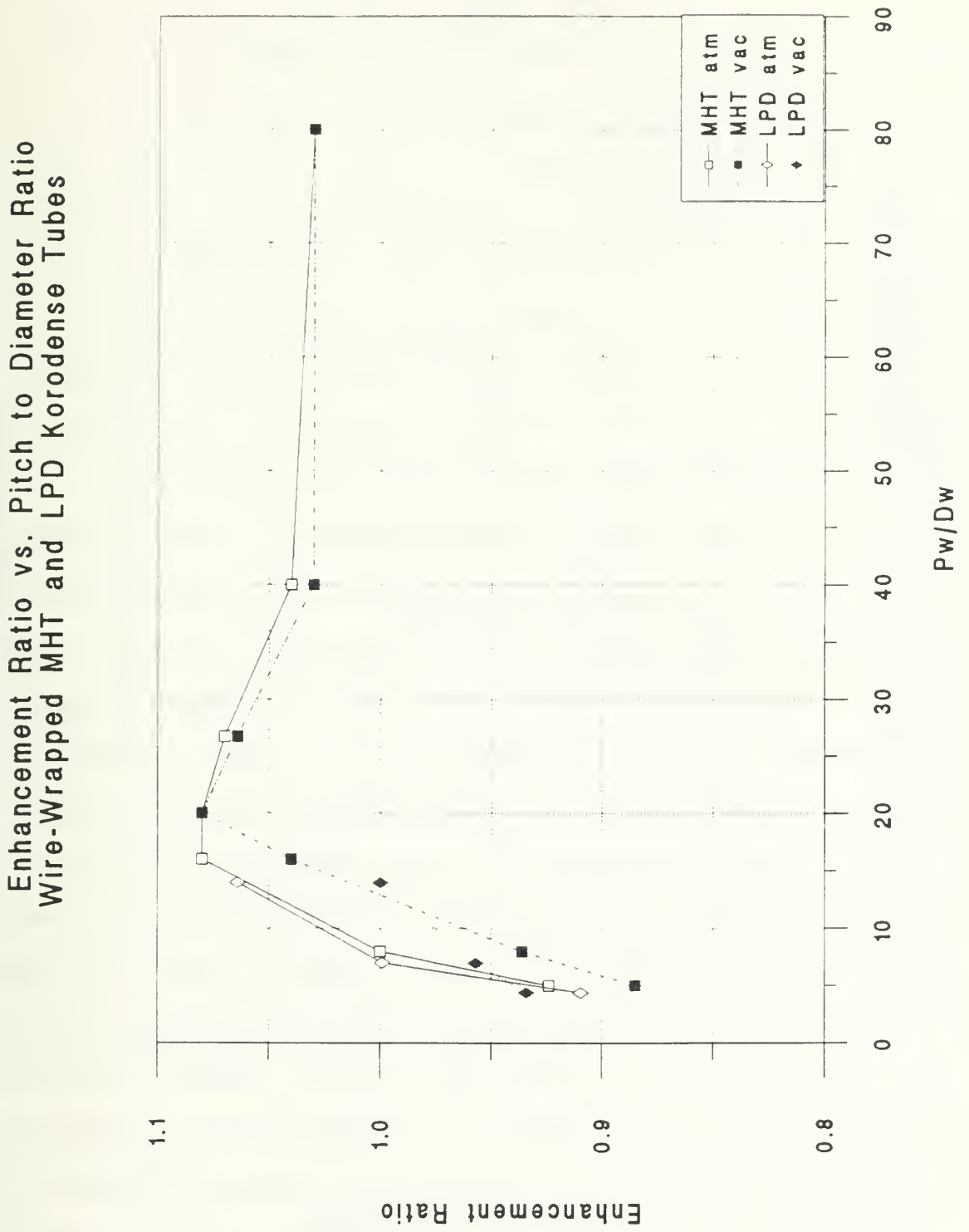

Figure 14. Enhancement Ratio vs. P_w/D_W for Wire-Wrapped Korodense Tubes

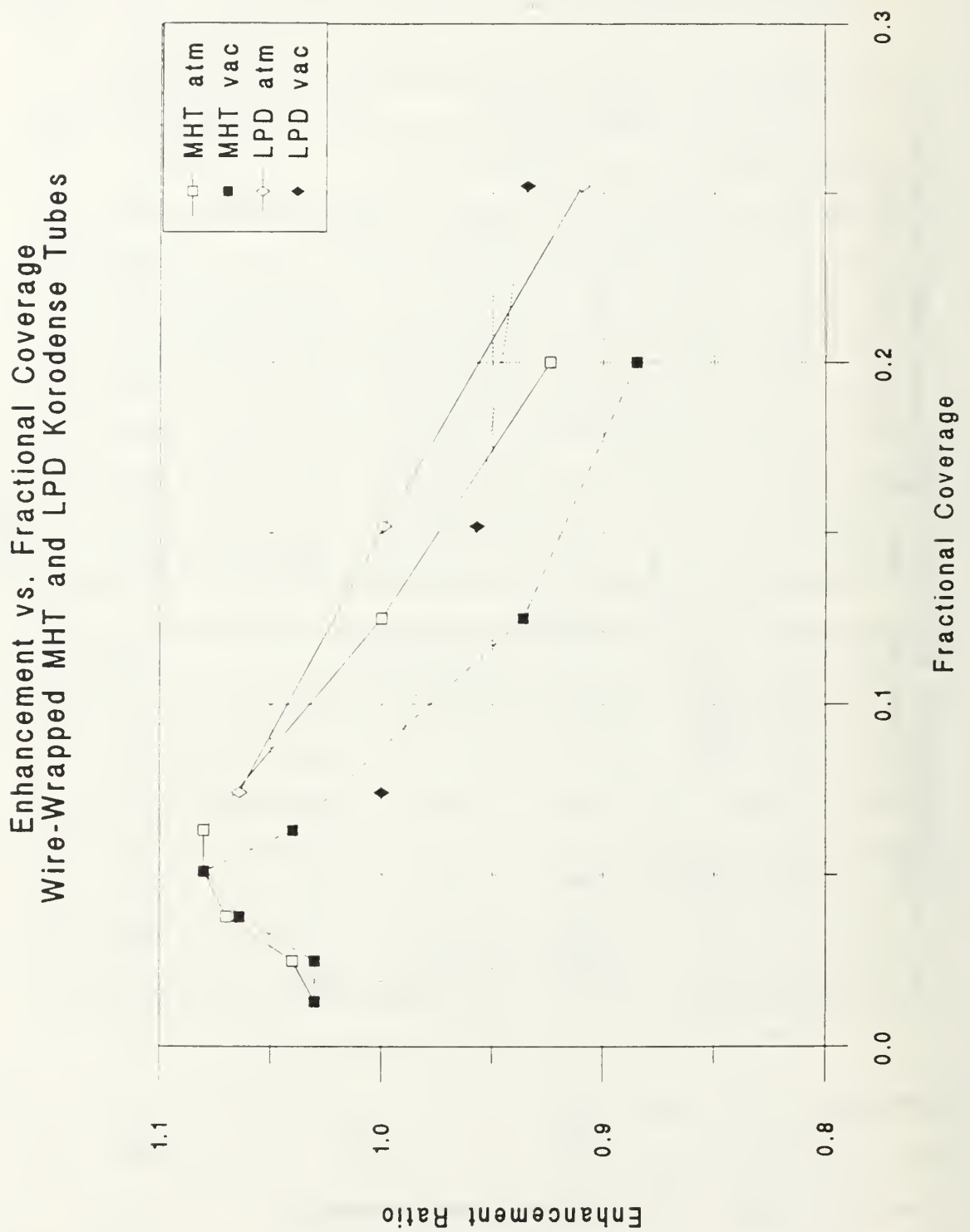

Figure 15. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense Tubes

data. His smallest wire diameter was only 0.5 mm.

The enhancement results obtained for the wire-wrapped MHT Korodense tube were also compared to a wire-wrapped smooth tube. Marto et al. [Ref. 31] reported an optimum wire pitch to diameter ratio ranging from 5 to 7 for wire-wrapped copper tubes. Sethumadhavan and Rao [Ref. 34] realized a maximum enhancement at a fractional coverage of 21%, corresponding to a $P_w/D_w \approx 5$. This value for P_w/D_w is much smaller than the optimum pitch to diameter ratio of 20 obtained in this study.

To further understand this relationship, data were compiled for wire-wrapped smooth tubes studied at NPS and compared with the current data in Figures 16 and 17. Both sets of data were plotted with constant pitch curves for a better comparison with the constant pitch results of the corrugated tubes. It can be seen that the wire-wrapped smooth copper and wire-wrapped smooth titanium tubes with P_w=4 mm have roughly the same slope. The same trend can be seen for the wire-wrapped smooth titanium and the wire-wrapped LPD and MHT tubes with a pitch of about 7 mm. Due to the limited data it is difficult to predict the optimal fractional coverage of the wire-wrapped smooth tubes for a constant wire pitch. However, it does appear to be less than the 21% obtained by Sethumadhavan and Rao [Ref. 34]. It can also be seen that the magnitude of the enhancements tend to vary with tube material and tube geometry. Mitrou's data [Ref. 14] for wire-wrapped smooth copper tubes show results 45 to 55% higher than the

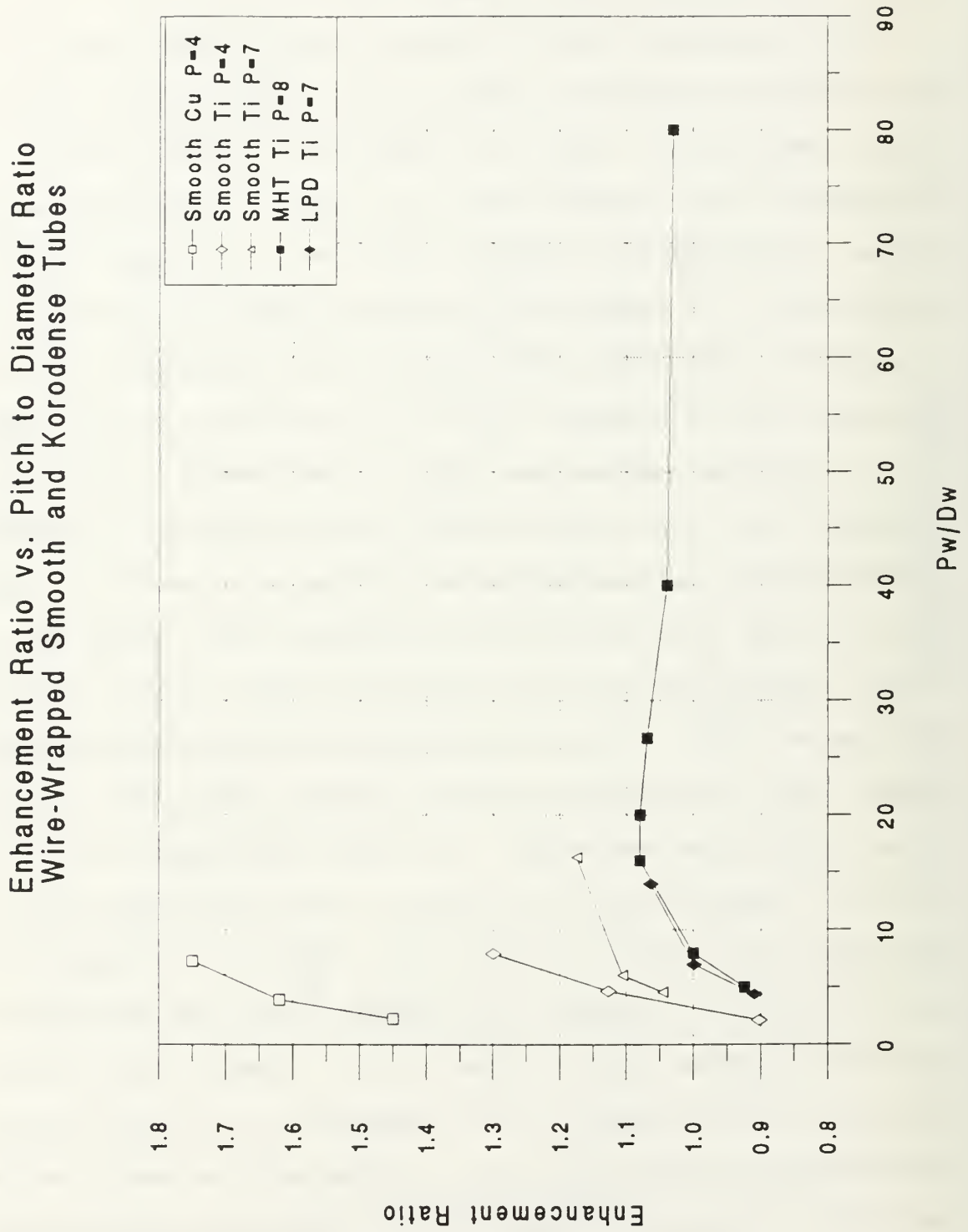

Figure 16. Enhancement Ratio vs. P_w/D_W for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes, NPS Data

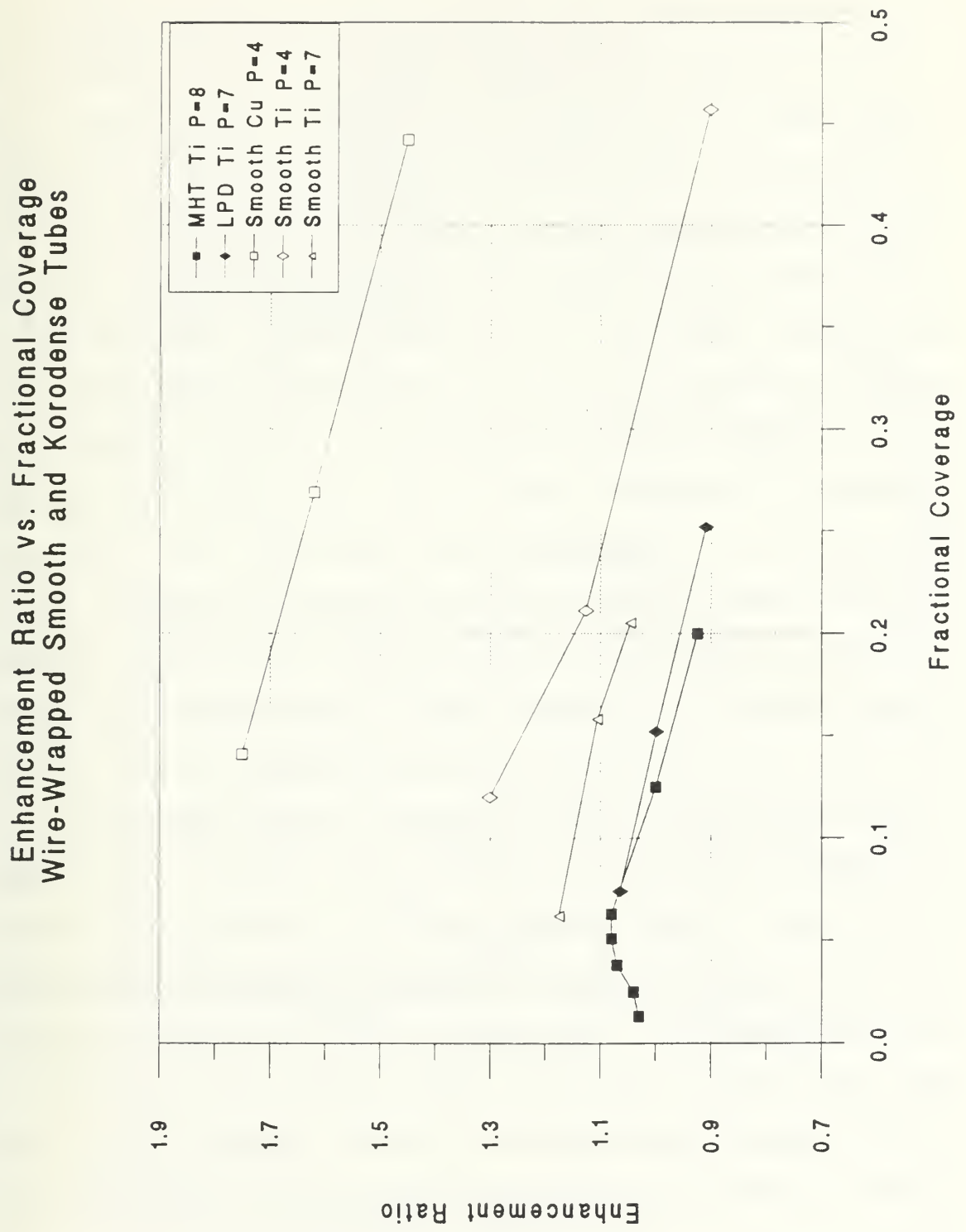

Figure 17. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes, NPS Data

wire-wrapped smooth titanium tube results for an equal pitch (P_w=4 mm) obtained by O'Keefe [Ref. 18]. This indicates that tubes made of materials with high thermal conductivities (such as copper) may provide additional enhancement characteristics. The effect of tube geometry can also be seen in the comparison of the wire-wrapped smooth titanium tube and the wire-wrapped LPD and MHT tubes (all with pitches ≈7 mm). The wire-wrapped smooth titanium tube achieved an enhancement ≈10% higher than the corrugated tubes of similar pitch. Figures 18 and 19 are identical to Figures 16 and 17 with the addition of the data obtained by Sethumadhavan and Rao [Ref. 34]. The tube material used in their tests is not known, but appears to have a thermal conductivity between copper and titanium (such as copper/nickel or aluminum). The most noticeable differences in their data and the data from research at NPS are the fractional coverage of the apparent maximum enhancement and the opposite slope of the constant pitch curves. This is most likely due the wire material used for wrapping their tubes. They used copper wire and all the NPS tubes were manufactured with titanium wire. The use of a highly conductive material may have produced more of a 'fin' effect with the wire and caused the peak enhancement to shift. Further study on the effect of the wire material is required to determine the effects.

Possible effects on the inside heat transfer coefficient due to wire-wrapping both smooth and corrugated tubes were

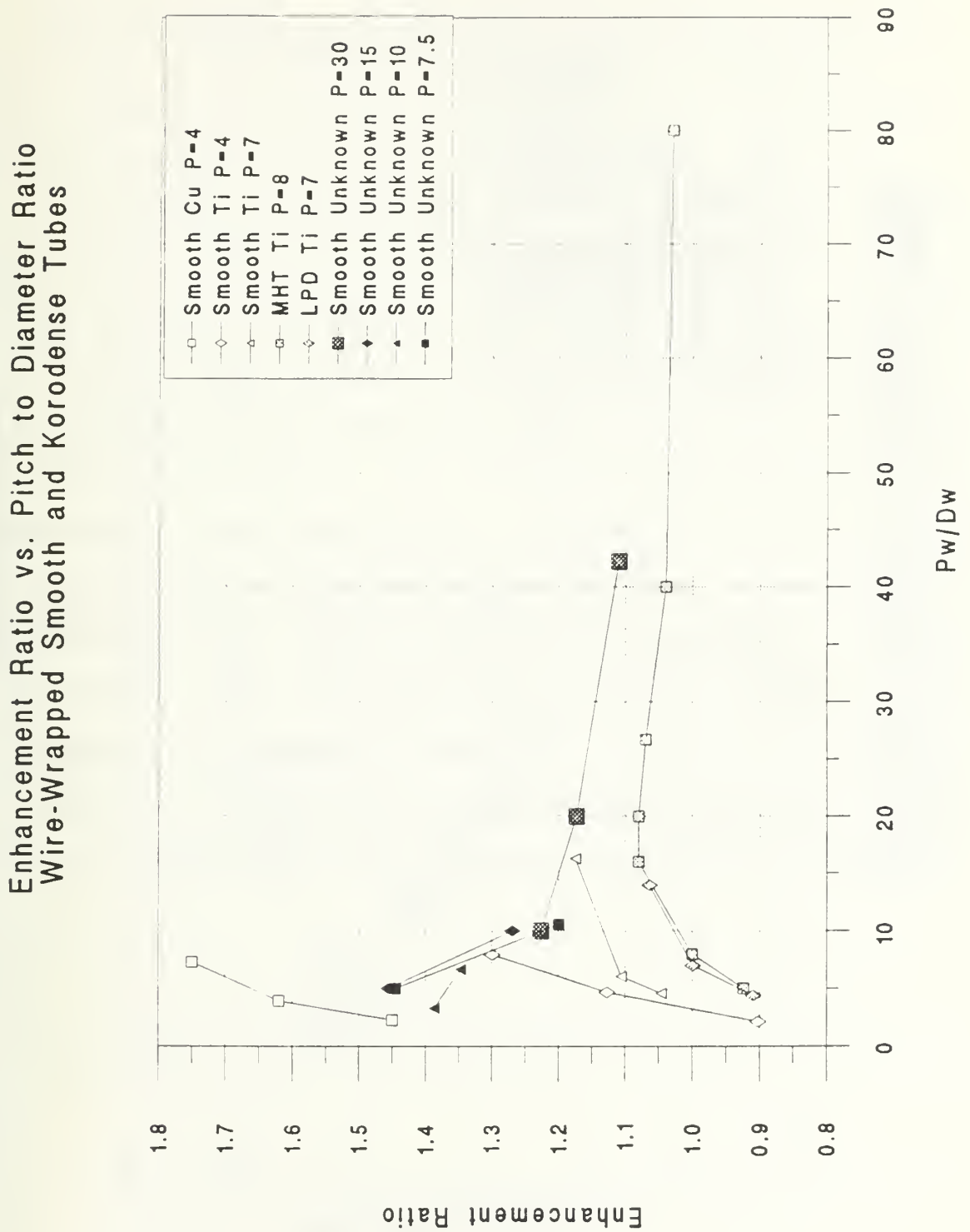

Figure 18. Enhancement Ratio vs. P_w/D_w for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes

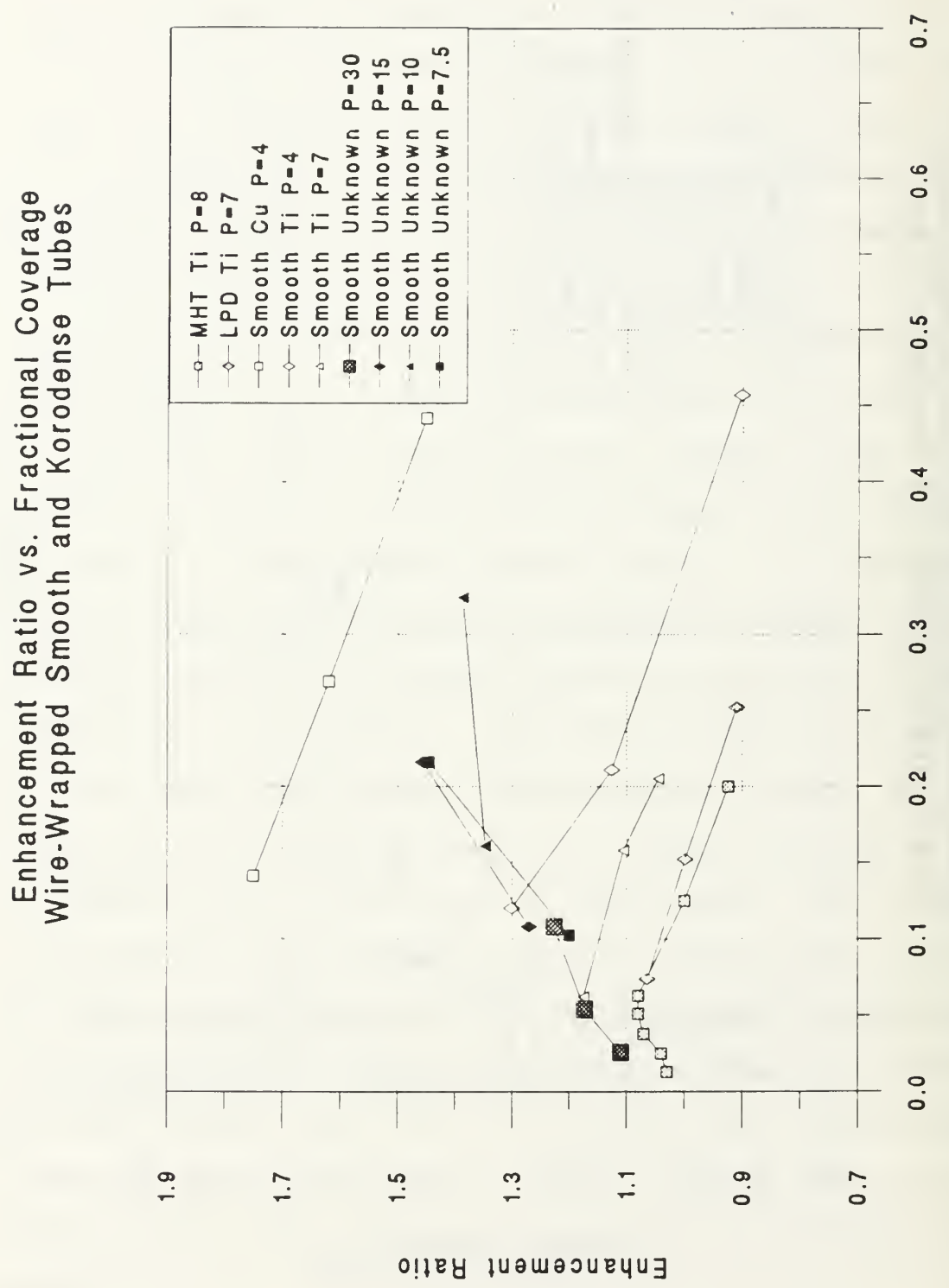

Figure 19. Enhancement Ratio vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes

also investigated. Figure 20 shows a possible decreasing trend in C_i with increasing fractional coverage. However, the magnitude of the decrease is minimal and the overall variation in C_i is within the uncertainty of the plain tube results.

In summary, the enhancement of the outside heat transfer coefficient for a titanium MHT Korodense tube over a smooth titanium tube was close to unity. The primary enhancement in the overall heat transfer coefficient was found to be due to an increase in the inside heat transfer coefficient, 21 to 26% above the LPD Korodense tube coefficient and 110 to 117% above the smooth tube coefficient. The effect of wire-wrapping corrugated tubes provides minimal additional enhancement to the outside heat transfer coefficient, a maximum of ≈8% with a $P_w/D_w \approx 20$ and a corresponding fractional coverage of 5%. However, the addition of wire-wrap into the grooves of a corrugated tube may have greater benefit when used in a tube bundle arrangement due to improved condensate drainage.

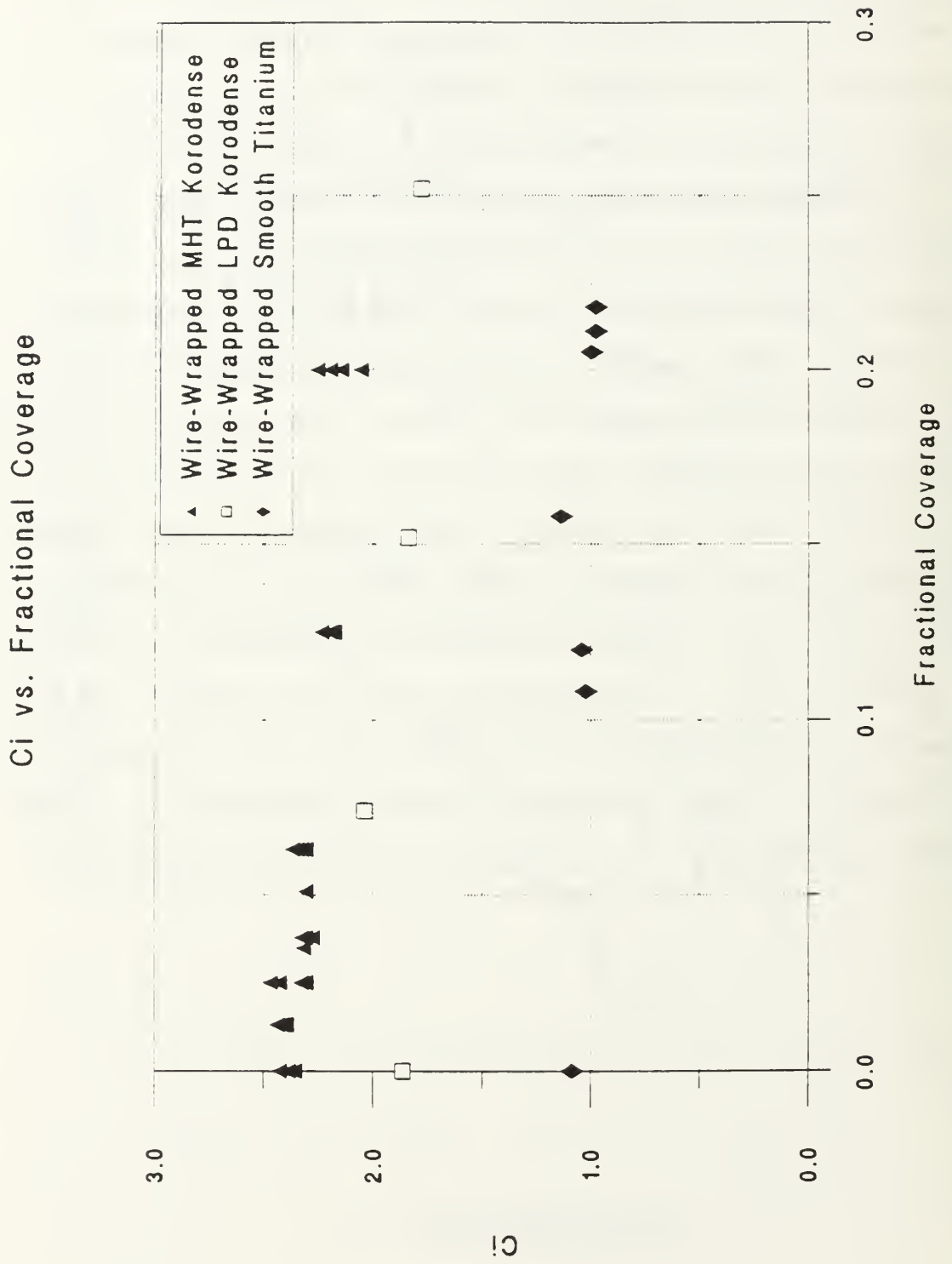

Figure 20. C_i vs. Fractional Coverage for Wire-Wrapped Korodense and Wire-Wrapped Smooth Tubes at Atmospheric Pressure

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Enhancement of the outside heat transfer coefficient due to the corrugation of the MHT Korodense titanium tube is near unity when compared to smooth tube results.

2. The corrugation of the MHT Korodense tube produces enhancements in the inside heat transfer coefficient from 110% to 117% above smooth tube results, and 21% to 26% above LPD Korodense tube results.

3. Wire-wrapping of MHT Korodense tubes yields minimal additional enhancement, ≈8%, when used in a single tube arrangement.

4. The optimal fractional coverage for the wire-wrapping of MHT Korodense tubes is ≈5% (P_w/D_w ≈20) when used in a single tube arrangement.

5. The thermal conductivity of the tube material effects the enhancement characteristics of wire-wrapped tubes.

6. Some relationship appears to exist between fractional coverage and the inside heat transfer coefficient.

7. The modified Wilson plot data reduction technique compensates for vapor velocity effects when using the Nusselt theory in determining the outside heat transfer coefficient.

B. RECOMMENDATIONS

1. Manufacture and test additional wire-wrapped LPD Korodense tubes with smaller wire diameters ranging from 0.1 mm to 0.4 mm to validate the trends found for the MHT Korodense tube.

2. Manufacture and test additional constant pitch wire-wrapped copper smooth tubes with wire diameters greater than 1.6 mm and less than 0.5 mm and determine the optimal wire diameter for specific wire pitches.

3. Test a set of wire-wrapped corrugated copper or copper/nickel tubes to determine the possible effect of

tube material on condensation, when compared to the titanium corrugated tubes.

4. Develop a numerical model to approximate the outside heat transfer characteristics for corrugated and wire-wrapped corrugated tubes.

5. Fabricate a set of corrugated tubes with outside electrical heater elements and conduct tests to validate the accuracy of the inside heat transfer correlations available for processing data on corrugated tubes with and without a HEATEX insert.

6. Input the Wolverine inside heat transfer correlation to the existing program. Reprocess selected corrugation tube data and compare results with those obtained by the Petukhov-Popov correlation.

7. Test wire-wrapped corrugated tubes in a tube bundle arrangement. Determine if additional overall bundle enhancement is possible with inundation effects included, and if the optimal fractional coverage shifts from that found for single tube tests.

8. Fabricate and test a set of multistart corrugated tubes with and without wire-wrapping to determine if additional enhancements can be realized using the multistart corrugation geometry.

9. Conduct additional tests on wire-wrapped smooth and corrugated tubes to determine if a relationship exists between fractional coverage and the inside heat transfer coefficient.

10. Test the enhancement effects of various wire materials when used for wire-wrapping smooth and corrugated tubes.

11. Investigate the possibility of bonding the wire-wrap to the tube surface and test the enhancement effects for smooth and corrugated tubes.

APPENDIX A. SYSTEM CORRECTIONS

A. FRICTIONAL TEMPERATURE CORRECTIONS

Coolant flowing through a tube experiences a temperature increase due to frictional heating. The magnitude of the temperature rise depends on the internal tube geometry and the velocity of the coolant. With the cooling water sump and the test section at ambient temperature, measurements were taken to determine the temperature increase due to frictional effects at flow rates ranging form 10% to 100% on the rotameter. Two separate runs were conducted for the MHT Korodense tube, one with the HEATEX insert installed and the second with no insert. Figure A. 1 show the results for the two runs. The data was curve fitted to a third order polynomial as shown in Table A. 1.

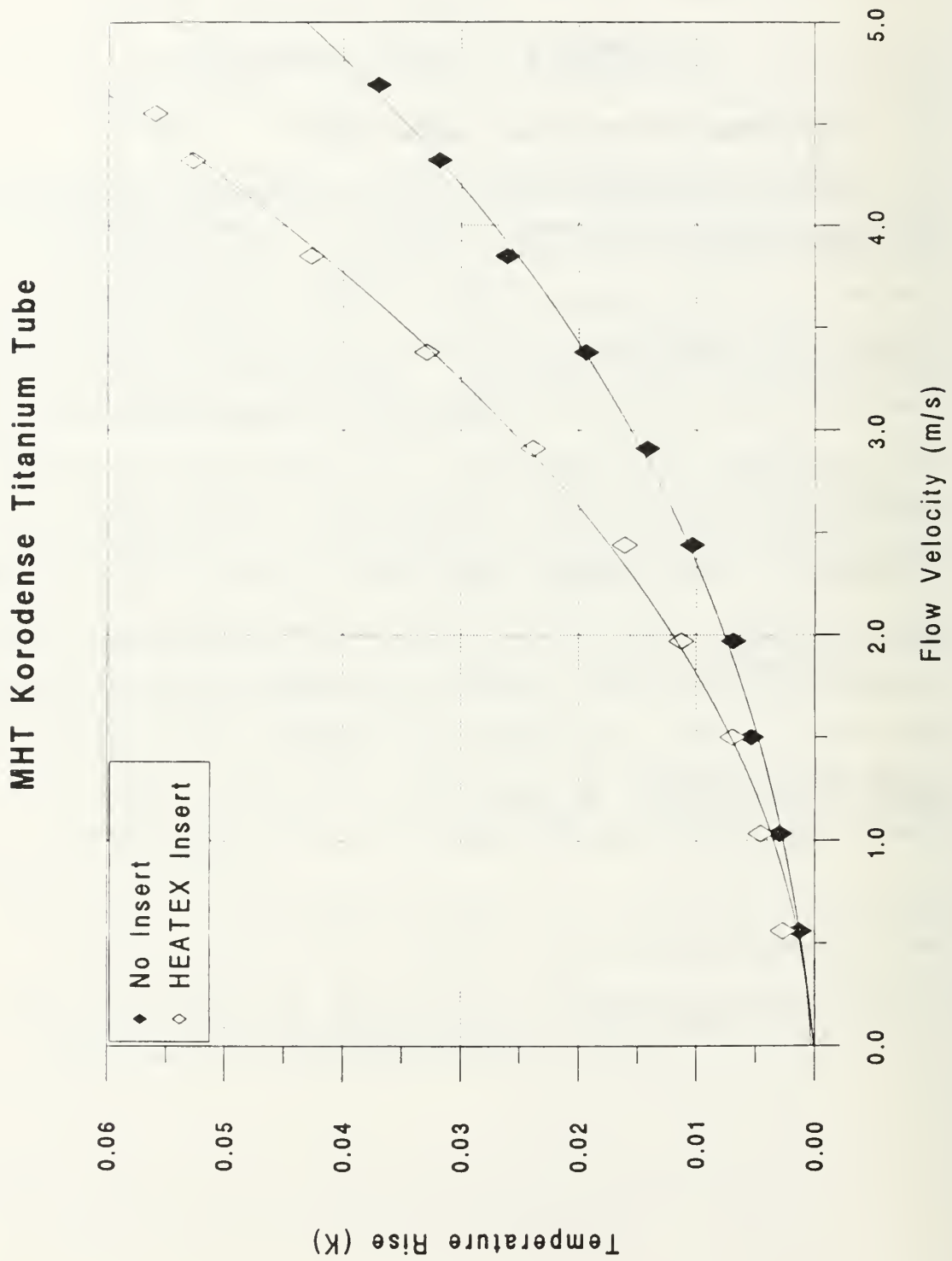

Figure A.1 Frictional Temperature Rise for the MHT Korodense Titanium Tube with and without a HEATEX Insert

Table A. 1 FRICTIONAL TEMPERATURE RISE EQUATIONS FOR MHT KORODENSE TUBE

Inside Condition	Polynomial Equation
HEATEX Insert	$T_{rise} = 2.564x10^{-4} + 6.263x10^{-4}V_w + 2.603x10^{-3}(V_w)^2 + 7.830x10^{-6}(V_w)^3$
No Insert	$T_{rise} = 6.790x10^{-5} + 1.632x10^{-3}V_w + 8.409x10^{-4}(V_w)^2 + 1.111x10^{-4}(V_w)^3$
where: T_{rise} = Temperature Rise (K) V_w = Fluid Velocity (m/s)	

APPENDIX B. UNCERTAINTY ANALYSIS

All derived quantities have an inherent uncertainty associated with them when their results are obtained from measured values. The uncertainty arises due to inaccuracies in the measurement of the physical quantities used in their calculations. The difference between the actual value and the measured value depends on the accuracy of the measuring device, the calibration of the device, and the experience of the operator. Eventhough the error associated with any single measurement may seem insignificant, it may have a profound effect on the accuracy of the derived quantity due to the calculations made.

Kline and McClintock [Ref. 67] developed a method to estimate the uncertainty in the derived quantity, R, which is a function of several measured variables, x_1, x_2, ..., x_n, as follows:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} W_1\right)^2 + \left(\frac{\partial R}{\partial x_2} W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} W_n\right)^2\right]^{1/2} \qquad \text{(B.1)}$$

where:

W_R is the uncertainty of the desired dependent variable

x_1, x_2, ..., x_n are the measured independent variables

W_1, W_2, ..., W_n are the uncertainties in the measured variables

Georgiadis [Ref. 68] presents a complete discussion on the uncertainty analysis used for this experiment. Based on Georgiadis' developments, Mitrou [Ref. 14] wrote a program for calculating the uncertainties in the mathematically derived quantities obtained from data collected using the apparatus utilized in this research. Modifications were made to the program which allow for the data collected on MHT Korodense tubes to be processed. Sample uncertainty results for the following data collection conditions are presented in this appendix.

1. Vacuum pressure with no insert and high flow rate (3.83 m/s).
2. Vacuum pressure with no insert and low flow rate (1.03 m/s).
3. Vacuum pressure with HEATEX insert and high flow rate (3.83 m/s).
4. Vacuum pressure with HEATEX insert and low flow rate (1.02 m/s).
5. Atmospheric pressure with no insert and high flow rate (3.82 m/s).
6. Atmospheric pressure with no insert and low flow rate (1.02 m/s).
7. Atmospheric pressure with HEATEX insert and high flow rate (3.82 m/s).
8. Atmospheric pressure with HEATEX insert and low flow rate (1.02 m/s).

1. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	LMNTNV8		
Pressure Condition:	Vacuum		
Vapor Temperature	=	48.574	(Deg C)
Water Flow Rate (%)	=	80.00	
Water Velocity	=	3.83	(m/s)
Heat Flux	=	1.481E+05	(W/m^2)
Tube-metal thermal conduc.	=	21.0	(W/m.K)
Petukov-Popov constant	=	2.3857	

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.09
Heat Flux, q	1.87
Log-Mean-Tem Diff, LMTD	1.63
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	2.48
Water-Side H.T.C., Hi	7.47
Vapor-Side H.T.C., Ho	6.77

2. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name:	LMNTNV8		
Pressure Condition:	Vacuum		
Vapor Temperature	=	48.691	(Deg C)
Water Flow Rate (%)	=	20.00	
Water Velocity	=	1.03	(m/s)
Heat Flux	=	1.149E+05	(W/m^2)
Tube-metal thermal conduc.	=	21.0	(W/m.K)
Petukov-Popov constant	=	2.3857	

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	2.99
Reynolds Number, Re	3.08
Heat Flux, q	3.07
Log-Mean-Tem Diff, LMTD	.56
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	3.13
Water-Side H.T.C., Hi	7.81
Vapor-Side H.T.C., Ho	13.98

3. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHV8
Pressure Condition: Vacuum
Vapor Temperature = 48.518 (Deg C)
Water Flow Rate (%) = 80.00
Water Velocity = 3.83 (m/s)
Heat Flux = 1.526E+05 (W/m^2)
Tube-metal thermal conduc. = 21.0 (W/m.K)
Petukov-Popov constant = 3.0112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.09
Heat Flux, q	1.83
Log-Mean-Tem Diff, LMTD	1.58
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	2.42
Water-Side H.T.C., Hi	5.92
Vapor-Side H.T.C., Ho	6.35

4. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHV8
Pressure Condition: Vacuum
Vapor Temperature = 48.551 (Deg C)
Water Flow Rate (%) = 20.00
Water Velocity = 1.02 (m/s)
Heat Flux = 1.202E+05 (W/m^2)
Tube-metal thermal conduc. = 21.0 (W/m.K)
Petukov-Popov constant = 3.0112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.00
Reynolds Number, Re	3.09
Heat Flux, q	3.08
Log-Mean-Tem Diff, LMTD	.54
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	3.12
Water-Side H.T.C., Hi	6.36
Vapor-Side H.T.C., Ho	11.54

5. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTNA8
Pressure Condition: Atmospheric (101 kPa)
Vapor Temperature = 99.954 (Deg C)
Water Flow Rate (%) = 80.00
Water Velocity = 3.32 (m/s)
Heat Flux = 3.959E+05 (W/m^2)
Tube-metal thermal conduc. = 21.0 (W/m.K)
Petukov-Popov constant = 2.4659

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.11
Heat Flux, q	1.10
Log-Mean-Tem Diff, LMTD	.61
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	1.26
Water-Side H.T.C., Hi	7.69
Vapor-Side H.T.C., Ho	4.97

6. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTNA8
Pressure Condition: Atmospheric (101 kPa)
Vapor Temperature = 99.981 (Deg C)
Water Flow Rate (%) = 20.00
Water Velocity = 1.02 (m/s)
Heat Flux = 3.114E+05 (W/m^2)
Tube-metal thermal conduc. = 21.0 (W/m.K)
Petukov-Popov constant = 2.4659

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.00
Reynolds Number, Re	3.10
Heat Flux, q	3.04
Log-Mean-Tem Diff, LMTD	.21
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	3.05
Water-Side H.T.C., Hi	8.04
Vapor-Side H.T.C., Ho	13.03

7. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHA8
Pressure Condition: Atmospheric (101 kPa)
Vapor Temperature = 99.924 (Deg C)
Water Flow Rate (%) = 80.00
Water Velocity = 3.82 (m/s)
Heat Flux = 4.083E+05 (W/m^2)
Tube-metal thermal conduc. = 21.0 (W/m.K)
Petukov-Popov constant = 3.3112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	0.80
Reynolds Number, Re	1.11
Heat Flux, q	1.09
Log-Mean-Tem Diff, LMTD	.53
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	1.24
Water-Side H.T.C., Hi	5.68
Vapor-Side H.T.C., Ho	4.25

8. DATA FOR THE UNCERTAINTY ANALYSIS:

File Name: LMNTHA8
Pressure Condition: Atmospheric (101 kPa)
Vapor Temperature = 99.999 (Deg C)
Water Flow Rate (%) = 20.00
Water Velocity = 1.02 (m/s)
Heat Flux = 3.367E+05 (W/m^2)
Tube-metal thermal conduc. = 21.0 (W/m.K)
Petukov-Popov constant = 3.3112

UNCERTAINTY ANALYSIS:

VARIABLE	PERCENT UNCERTAINTY
Mass Flow Rate, Md	3.00
Reynolds Number, Re	3.11
Heat Flux, q	3.04
Log-Mean-Tem Diff, LMTD	.19
Wall Resistance, Rw	4.97
Overall H.T.C., Uo	3.05
Water-Side H.T.C., Hi	6.14
Vapor-Side H.T.C., Ho	9.73

APPENDIX C. DRPML PROGRAM LISTING

The data collection and reduction program, DRPML, which was used throughout this study follows:

```
1000! DRPML (LONG)
1006! REVISED FROM DRPCH:   SEP 1992  O'KEEFE)
1007!
1008! TO BE USED WITH NON-INSTRUMENTED TUBES ONLY
1009! TAKES DATA IN THE FORMAT OF SWENSEN/O'KEEFE/LONG
1010! CAN REPROCESS ANY NON-INSTRUMENTED DATA
1012!
1013! THIS PROGRAM WAS USED TO COLLECT ALL THE NON-
1014! INSTRUMENTED DATA TAKEN BY LONG (JAN-JUN 1993) FOR TITANIUM TUBES
1015!
1017!    MEANING OF ALL FLAGS IN PROGRAM
1018!
1019!    IFT:   FLUID TYPE
1020!    ISO:   OPTION WITHIN PROGRAM
1021!    IM:    INPUT MODE
1022!    IWIL:  VALUE OF C1 USED
1023!    IFG:   FINNED OR SMOOTH
1024!    INN:   INSERT TYPE
1025!    IWT:   LOOP NO. WITHIN PROGRAM
1026!    IWTH:  ALTERNATIVE CONDENSER TUBES
1027!    IMC:   TUBE MATERIAL
1028!    ITDS:  TUBE DIAMETER
1029!    IPC:   PRESSURE CONDITION
1030!    INF:   DIMENSIONLESS FILE REQUIRED
1031!    IPF:   PLOT FILE REQUIRED
1032!    IOV:   OUTPUT REQUIRED
1033!    IHI:   INSIDE HTC CORRELATION
1034!    IOC:   OUTSIDE HTC THEORY/CORRELATION
1035  COM /Cc/ C(7)
1036  COM /Cc55/ T55(5)
1037  COM /Cc56/ T56(5)
1038  COM /Cc57/ T57(5)
1039  COM /Cc58/ T58(5)
1040  COM /Fld/ Ift,Istu
1041  DIM Emf(20),Tw(6)
1042  COM /Pr/ Qpa(42),Tfm(42),Tfmr,Ipc,Qpr
1043  COM /Wil/ Nrun,Itm,Iwth,Imc,Ife,Ijob,Iwd,Ifg,Ipco,Ifto,Iwil,Ihi,Ioc,Inam,K
cu,Re.p,Rm,Ax
1044  COM /Geom/ D1,D2,Di,Do,L,L1,L2
1045  COM /Fric/ Istuo,Inn,Iwtho,Vw,Vws,Inamo
1047  DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1048  DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1049  READ C(*)
1050  DATA 273.15,2.5943E-2,-7.2671E-7,3.2941E-11,-9.7719E-16,9.7121E-20
1051  READ T55(*)
1052  DATA 273.15,2.5878E-2,-5.9853E-7,-3.1242E-11,1.3275E-14,-1.0188E-18
```

```
1053  READ T56(*)
1054  DATA 273.15,2.5923E-2,-7.3933E-7,2.8625E-11,1.9717E-15,-2.2486E-19
1055  READ T57(*)
1056  DATA 273.15,2.5931E-2,-7.5232E-7,4.0657E-11,-1.2791E-15,6.4402E-20
1057  READ T58(*)
1058  Dr=.015875    ! Outside diameter of the outlet end
1059  Dssp=.1524    ! Inside diameter of stainless steel test section
1060  Ax=PI*Dssp^2/4
1061  Alp2=0.
1062  L=.13335      ! Condensing length
1063  L1=.060325    ! Inlet end "fin length"
1064  L2=.034925    ! Outlet end "fin length"
1065  PRINTER IS 1
1066  BEEP
1067  PRINT USING "4X,'""Select option:"""
1069  PRINT USING "6X,"" 0 Take data or re-process previous data"""
1090  PRINT USING "6X,"" 2 WILSON Analysys'""
1106  INPUT Iso
1108  Iso=Iso+1
1111  IF Iso 1 THEN 3094
1112  BEEP
1115  INPUT "SELECT FLUID (0=WATER, 1=R-113, 2=EG)",Ift
1116  Ifto=Ift
1117  BEEP
1118  Ijob=0
1119  INPUT "ENTER INPUT MODE (0=3054A,1=FILE)",Im
1120  Im=Im+1
1123  BEEP
1124  IF Im=1 THEN
1126     INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1129     OUTPUT 709;"TD";Date$
1132     OUTPUT 709;"TD"
1133     ENTER 709;Date$
1135  END IF
1136  IF Ijob=1 THEN
1138     BEEP
1141     INPUT "SKIP PAGE AND HIT ENTER",Ok
1144  END IF
1145  PRINTER IS 701
1146  IF Im=1 THEN
1148     ENTER 709;Date$
1150     PRINT "          Month, date and time :";Date$
1151  END IF
1153  PRINT
1156  PRINT USING "10X,""NOTE: Program name : DRPML"""
1171  IF Ijob=1 THEN 1189
```

```
1174  BEEP
1186  INPUT "SELECT (C:0=FIND,1=STORED C:)",Iwrl
1189  IF Im=1 THEN
1192     BEEP
1195     INPUT "GIVE A NAME FOR THE RAW DATA FILE",D_file$
1198     PRINT USING "15x,""File name    : "",14A";D_file$
1201     CREATE BDAT D_file$,30
1204     ASSIGN @File TO D_file$
1207     BEEP
1210     INPUT "ENTER GEOMETRY CODE (1=FINNED,0=PLAIN)",Ifg
1211     Inn=0
1212     PRINTER IS 1
1216     BEEP
1217     PRINT "   ENTER INSERT TYPE:"
1218     PRINT "       0=NONE (DEFAULT)"
1219     PRINT "       1=TWISTED TAPE"
1220     PRINT "       2=WIRE WRAP"
1221     PRINT "       3=HEATEX"
1222     INPUT Inn
1225     OUTPUT @File;Ifg,Inn
1227     Iwt=0  ! FOR UNINSTRUMENTED TUBE
1228     Fh=0
1231     Fp=0
1234     Fw=0
1235     Istu=0
1236     Istuo=Istu
1238     IF Ifg=0 THEN 1241
1239     INPUT "FIN PITCH, HEIGHT AND WIDTH IN MM, Fp,Fh,Fw",Fp,Fh,Fw
1241     OUTPUT @File;Iwt,Fp,Fw,Fh
1242  ELSE
1249     BEEP
1250     PRINTER IS 1
1252     PRINT "  STUDENT'S DATA TO BE REPROCESSED:"
1253     PRINT "  0=SWENSEN/O'KEEFE/LONG (DEFAULT)"
1254     PRINT "  1=VAN PETTEN/MITROU/COUMES/GUTTENDORF"
1255     INPUT Istu
1256     Istuo=Istu
1258     BEEP
1259     PRINT
1260     IF Istu=1 THEN
1261        PRINT " STUDENT NAME:"
1262        PRINT " 0=VAN PETTEN"
1263        PRINT " 1=MITROU"
1264        PRINT " 2=COUMES"
1265        PRINT " 3=GUTTENDORF"
1266     ELSE
```

```
1267          PRINT " 4=SWENSEN"
1268          PRINT " 5=O'KEEFE"
1269          PRINT " 6=LONG"
1271       END IF
1272       INPUT Inam
1273       Inamo=Inam
1275       BEEP
1276       INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
1277       PRINTER IS 701
1278       IF Inam=0 THEN PRINT USING "16X,""Data taken by                : VAN PETT
EN"""
1279       IF Inam=1 THEN PRINT USING "16X,""Data taken by                : MITROU""
"
1280       IF Inam=2 THEN PRINT USING "16X,""Data taken by                : COUMES""
"
1281       IF Inam=3 THEN PRINT USING "16X,""Data taken by                : GUTTENDO
RF"""
1282       IF Inam=4 THEN PRINT USING "16X,""Data taken by                : SWENSEN"
""
1283       IF Inam=5 THEN PRINT USING "16X,""Data taken by                : O'KEEFE"
""
1284       IF Inam=6 THEN PRINT USING "16X,""Data taken by                : LONG"""
1285       PRINT USING "16X,""This analysis done on file : "",10A";D_file$
1286       PRINTER IS 1
1287       BEEP
1288       INPUT "ENTER NUMBER OF DATA SETS STORED",Nrun
1289       ASSIGN @File TO D_file$
1290       ENTER @File;Ifg,Inn
1291       IF Istu=0 THEN
1292          ENTER @File;Iwt,Fp,Fw,Fh
1293       ELSE
1294          IF Ifg=0 THEN ENTER @File;Iwt
1295          IF Ifg=1 THEN ENTER @File;Fp,Fw,Fh
1296       END IF
1297    END IF
1298    IF Ijob=1 THEN 1537
1299    IF Ift.0 THEN 1345
1300    BEEP
1301    PRINTER IS 1
1302    PRINT USING "4X,""Select tube type:"""
1303    PRINT USING "6X,""0 Copper Tube"""
1306    PRINT USING "6X,""1 Wolverine Korodense LPD Titanium Tube"""
1320    PRINT USING "6X,""2 Smooth Titanium Tube"""
1321    PRINT USING "6X,""3 Wolverine Korodense MHT Titanium Tube"""
1323    INPUT Iwth
1324    Iwtho=Iwth
```

```
1326  BEEP
1327  PRINT USING "4X,""Select tube Enhancement used:"""
1328  PRINT USING "6X,""0 SMOOTH TUBE"""
1329  PRINT USING "6X,""1 FINNED TUBE"""
1330  PRINT USING "6X,""2 WIRE-WRAPPED SMOOTH TUBE"""
1331  PRINT USING "6X,""3 LPD KORODENSE TUBE"""
1332  PRINT USING "6X,""4 WIRE-WRAPPED LPD KORODENSE TUBE"""
1333  PRINT USING "6X,""5 MHT KORODENSE TUBE"""
1334  PRINT USING "6X,""6 WIRE-WRAPPED MHT KORODENSE TUBE"""
1335  INPUT Ityp
1336  PRINTER IS 701
1337  BEEP
1338  PRINTER IS 1
1339  PRINT USING "4X,""Select Material Code:"""
1340  PRINT USING "6X,""0 Copper    1 Stainless steel"""
1341  PRINT USING "6X,""2 Aluminum  3 90:10 Cu-Ni"""
1342  PRINT USING "6X,""4 Titanium """
1343  INPUT Imc
1345  PRINTER IS 1
1348  BEEP
1349  Itds=1
1351  IF Iwth=0 THEN
1352     PRINT USING "4X,""SELECT TUBE DIA TYPE:"""
1357     PRINT USING "6X,""0  SMALL"""
1360     PRINT USING "6X,""1  MEDIUM (DEFAULT)"""
1363     PRINT USING "6X,""2  LARGE"""
1366     INPUT Itds
1367  END IF
1369  PRINTER IS 701
1372  IF Iwth=0 THEN
1375     Di=.0127      ! ID OF MEDIUM & LARGE TUBES
1378     Do=.01905     ! OD OF MEDIUM TUBE
1383  END IF
1384  IF Iwth=1 THEN
1399     Di=.01347
1402     Do=.01585
1405  END IF
1457  IF Iwth=2 THEN
1458     Do=.01585
1459     Di=.01386
1460  END IF
1461  IF Iwth=3 THEN
1462     Do=.01607
1463     Di=.01353
1464  END IF
1466  D1=.01905
```

```
1467  D2=.01587
1468  IF Itds=0 THEN
1469     Do=.0127
1471     D1=.009525
1474  END IF
1477  IF Itds=2 THEN Do=.025
1478  IF Iwth=1 OR Iwth=3 THEN D1=.01585
1479  IF Iwth=1 OR Iwth=3 THEN D2=.01585
1484  IF Iwth=2 THEN D1=.01587
1485  IF Iwth=2 THEN D2=.01587
1487  IF Imc=0 THEN Kcu=385
1489  IF Imc=1 THEN Kcu=16
1492  IF Imc=2 THEN Kcu=167
1495  IF Imc=3 THEN Kcu=45
1497  IF Imc=4 THEN Kcu=21.0
1498  Rm=Do*LOG(Do/D1)/(2*Kcu)  ! wall resistance based on outside area
1501  BEEP
1504  INPUT "ENTER PRESSURE CONDITION (0=V,1=A)",Ipc
1507  Ipco=Ipc
1508  Inf=0
1510  BEEP
1537  Ife=1
1538  PRINTER IS 701
1543  PRINT USING "16X,""This analysis includes end-fin effect"""
1546  PRINT USING "16X,""Thermal conductivity      = "",3D.D,"" (W/m.K)""";Kcu
1549  PRINT USING "16X,""Inside diameter, Di       = "",DD.DD,"" (mm)""";D1*1000
1552  PRINT USING "16X,""Outside diameter, Do      = "",DD.DD,"" (mm)""";Do*1000
1556  Ih1=0
1557  PRINTER IS 1
1558  PRINT "     SELECT INSIDE CORRELATION:"
1559  PRINT "          0=SIEDER-TATE (DEFAULT)"
1560  PRINT "          1=SLEICHER-ROUSE"
1561  PRINT "          2=PETUKHOV-POPOV"
1562  INPUT Ih1
1563  IF Ih1=0 THEN
1564     BEEP
1566     INPUT "     SELECT REYNOLDS EXPONENT",Rexp
1567  END IF
1568  Ioc=0
1569  BEEP
1570  PRINT
1571  PRINT "     SELECT OUTSIDE THEORY/CORRELATION FOR WILSON ANALYSIS:"
1572  PRINT "          0=NUSSELT THEORY (DEFAULT)"
1573  PRINT "          1=FUJII (1979) CORRELATION"
1574  INPUT Ioc
1575  BEEP
```

```
1576  Itm=1
1577  PRINT
1578  PRINT "    SELECT COOLANT TEMPERATURE RISE MEASUREMENT:"
1579  IF Istu=0 THEN PRINT "         0=SINGLE TEFLON T/C"
1580  PRINT "         1=QUARTZ THERMOMETER (DEFAULT)"
1581  PRINT "         2=10-JUNCTION THERMOPILE"
1582  INPUT Itm
1583  PRINTER IS 701
1584  IF Itm=0 THEN PRINT USING "16X,""This analysis uses the SINGLE TEFLON T/C
readings"""
1585  IF Itm=1 THEN PRINT USING "16X,""This analysis uses the QUARTZ THERMOMETER
 readings"""
1586  IF Itm=2 THEN PRINT USING "16X,""This analysis uses the 10-JUNCTION THERMO
PILE readings"""
1587  Iic=1 ! FOR MODIFIED WILSON
1588  IF Ihi=0 THEN Ci=.027
1595  IF Ihi=1 THEN Ci=1.
1596  IF Ihi=2 THEN Ci=1.
1599  IF Iwil=1 THEN
1601     BEEP
1602     INPUT "ENTER Ci IF DIFFERENT FROM STORED VALUE",Ci
1603  END IF
1604  PRINTER IS 701
1605  IF Ihi=0 THEN PRINT USING "16X,""Modified Sieder-Tate coefficient   = "",Z
.4D";Ci
1606  IF Ihi=0 THEN PRINT USING "16X,""Chosen Reynolds No. exponent       = "",D
.DD";Rexp
1607  IF Ihi=1 THEN PRINT USING "16X,""Modified Sleicher-Rouse coefficient   = "
",Z.4D";Ci
1608  IF Ihi=2 THEN PRINT USING "16X,""Modified Petukhov-Popov coefficient   = "
",Z.4D";Ci
1609  IF Inn=0 THEN PRINT USING "16X,""Using no insert inside tube"""
1610  IF Inn=2 THEN PRINT USING "16X,""Using wire wrap insert inside tube"""
1611  IF Inn=3 THEN PRINT USING "16X,""Using HEATEX insert inside tube"""
1612  IF Istu=0 THEN
1613     IF Inn=1 THEN PRINT USING "16X,""Using twisted tape insert inside tube"
""
1614  ELSE
1615     IF Inn=1 THEN PRINT USING "16X,""Using wire wrap insert inside tube"""
1616  END IF
1619  IF Iic=0 AND Ife=1 THEN Ac=26.4
1620  IF Iic=1 THEN Ac=0.
1621  BEEP
1622  IF Ijob=1 THEN 1648
1623  PRINTER IS 1
16241 INPUT "NAME FOR A TEMPORARY PLOT FILE (TO BE PURGED)",P_file$
```

```
1625  P_file$="DUMMY"
1626  BEEP
1634  CREATE BDAT P_file$,10
1644  ASSIGN @File TO P_file$
1648  IF Ijob=1 THEN
1651     Iov=1
1654     GOTO 1667
1657  END IF
1660  BEEP
1661  INPUT "SELECT OUTPUT (0=SHORT, 1=LONG)",Iov
1666  Iov=Iov+1
1667  PRINTER IS 701
1672  IF Ityp=0 THEN PRINT USING "16X,""Tube Enhancement    : SMOOTH TUBE"""
1673  IF Ityp=1 THEN PRINT USING "16X,""Tube Enhancement    : FINNED TUBE"""
1674  IF Ityp=2 THEN PRINT USING "16X,""Tube Enhancement    : WIRE-WRAPPED SMOOTH
 TUBE"""
1675  IF Ityp=3 THEN PRINT USING "16X,""Tube Enhancement    : LPD KORODENSE TUBE"
""
1678  IF Ityp=4 THEN PRINT USING "16X,""Tube Enhancement    : WIRE-WRAPPED LPD KO
RODENSE TUBE"""
1679  IF Ityp=5 THEN PRINT USING "16X,""Tube Enhancement    : MHT KORODENSE TUBE"
""
1680  IF Ityp=6 THEN PRINT USING "16X,""Tube Enhancement    : WIRE-WRAPPED MHT KO
RODENSE TUBE"""
1682  BEEP
1683  IF Imc=0 THEN PRINT USING "16X,""Tube material       : COPPER"""
1684  IF Imc=1 THEN PRINT USING "16X,""Tube material       : STAINLESS-STEEL"""
1685  IF Imc=2 THEN PRINT USING "16X,""Tube material       : ALUMINUM"""
1686  IF Imc=3 THEN PRINT USING "16X,""Tube material       : 90/10 CU/NI"""
1687  IF Imc=4 THEN PRINT USING "16X,""Tube material       : TITANIUM"""
1688  IF Ipc=0 THEN PRINT USING "16X,""Pressure condition : VACUUM"""
1689  IF Ipc=1 THEN PRINT USING "16X,""Pressure condition : ATMOSPHERIC"""
1690  PRINT USING "16X,""Fin pitch, width, and height (mm): "",DD.DD,2X,Z.DD,2X,
Z.DD";Fp,Fw,Fh
1691  IF (Iwil=0 OR Iwil=2) AND Im=2 THEN
1692     Ijob=1
1693     Iwd=1
1696     CALL Wilson(C1)
1699  END IF
1702  J=0
1712  IF Iov=1 THEN
1722     PRINT
1723     IF Ih1=1 THEN
1724        PRINT USING "10X,""Data  Vw      Uo          Ho        Qp        Tcf
   Ts    Rexp"""
1725        PRINT USING "10X,""  # (m/s)  (W/m^2-K)  (W/m^2-K)   (W/m^2)   (C)
```

```
                S-R)""
1726      ELSE
1728         PRINT USING "10X,""Data     Vw        Uo             Ho            Qp
     Taf      Ts""
1729         PRINT USING "10X,""  #     (m/s)    W/m 2-K)      W/m 2-K)    (W/m 2-
     C)      C)""""
1730      END IF
1740   END IF
1747   Zx=0
1750   Zx2=0
1753   Zxy=0
1756   Zy=0
1759   Sx=0
1762   Sy=0
1765   Sxs=0
1768   Sxy=0
1771   Go_on=1
1774 Repeat:!
1777   J=J+1
1780   IF Im=1 THEN
1783      BEEP
1786      INPUT "LIKE TO CHECK NG CONCENTRATION (1=Y,0=N)?",Ng
1789      IF J=1 THEN
1792         OUTPUT 709;"AR AF40 AL41 VR5"
1795         OUTPUT 709;"AS SA"
1798      END IF
1801      BEEP
1804      INPUT "ENTER FLOWMETER READING",Fm
1807      OUTPUT 709;"AR AF60 AL62 VR5"
1810      OUTPUT 709;"AS SA"
1813      ENTER 709;Etp
1816      OUTPUT 709;"AS SA"
1819      BEEP
1822      INPUT "CONNECT VOLTAGE LINE",Ok
1825      ENTER 709;Bvol
1828      BEEP
1831      INPUT "DISCONNECT VOLTAGE LINE",Ok
1834      IF Bvol<.1 THEN
1837         BEEP
1840         BEEP
1843         INPUT "INVALID VOLTAGE, TRY AGAIN!",Ok
1846         GOTO 1819
1849      END IF
1858      OUTPUT 709;"AS SA"
1861      ENTER 709;Bamp
1862      Etp=Etp*1.E+6
```

```
1863      OUTPUT 709;"AR AF40 AL47 VRS"
1874      Nn=7
1875      FOR I=0 TO Nn
1879         OUTPUT 709;"AS SA"
1885         Se=0
1888         FOR K=1 TO 10
1891            ENTER 709;E
1894            Se=Se+E
1897         NEXT K
1900         Emf(I)=ABS(Se/10)
1916         Emf(I)=Emf(I)*1.E+6
1918      NEXT I
1921      OUTPUT 709;"AS SA"
1924      OUTPUT 713;"T1R2E"
1927      WAIT 2
1930      ENTER 713;T11
1933      OUTPUT 713;"T2R2E"
1936      WAIT 2
1939      ENTER 713;T2
1942      OUTPUT 713;"T1R2E"
1945      WAIT 2
1948      ENTER 713;T12
1951      T1=(T11+T12)*.5
1954      OUTPUT 713;"T3R2E"
1960      BEEP
1970      INPUT "ENTER PRESSURE GAGE READING (Pga)",Pga
1971      Pvap1=Pga*6894.7 ! PSI TO Pa
1972      OUTPUT 709;"AR AF64 AL64 VRS"
1973      OUTPUT 709;"AS SA"    ! PRESSURE TRANSDUCER
1974      Ss=0
1975      FOR K=1 TO 20
1976         ENTER 709;Etran
1977         Ss=Ss+Etran
1978      NEXT K
1979      Ptran=ABS(Ss/20)
1980      BEEP
1981      PRESSURE IN Pa FROM TRANSDUCER
1982      Pvap2=(-2.93604*Ptran+14.7827)*6894.7
1985   ELSE
1986      IF Istu=0 THEN
1989         ENTER @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
1990      ELSE
1992         ENTER @File;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),F
m,T1,T2,Phg,Pwater
1994      END IF
1996      IF J=1 OR J=20 OR J=Nrun THEN
```

```
1997        Ng=1
1998     ELSE
1999        Ng=0
2000     END IF
2002  END IF
2003  IF Istu=0 THEN
2008     Tsteam1=FNTvsv57(Emf(0))
2009     Tsteam1=Tsteam1-273.15
2010     Tsteam2=FNTvsv56(Emf(1))
2011     Tsteam2=Tsteam2-273.15
2012     Tsteam=Tsteam1
2015     Troom=FNTvsv58(Emf(2))
2023     Troom=Troom-273.15
2038     Tcon=FNTvsv58(Emf(7))
2039     Tcon=Tcon-273.15
2042  ELSE
2043     Tsteam=FNTvsv(Emf(0))
2044     Troom=FNTvsv(Emf(3))
2045     Tcon=FNTvsv(Emf(4))
2046  END IF
2048  Psat=FNPvst(Tsteam)
2050  Rohg=13529-122*(Troom-26.85)/50
2053  Rowater=FNRhow(Troom)
2063  IF Istu=0 THEN
2081     Ptest1=Pvap1
2082     Ptest2=Pvap2
2083  ELSE
2084     Ptest2=(Phg*Rohg-Pwater*Rowater)*9.81/1000
2085  END IF
2087  Pks=Psat*1.E-3
2088  Pkp=Ptest2*1.E-3
2089  Pkt=Pks
2092  Tsat=FNTvsp(Psat)
2098  Vst=FNVvst(Tsteam)
2104  Ppng=(Ptest2-Psat)/Ptest2
2121  Ppst=1-Ppng
2122  Mwv=18.016
2123  IF Ift=1 THEN Mwv=137    ' TO BE CORRECTED
2124  IF Ift=2 THEN Mwv=62
2125  Vfng=(Ptest2-Psat)/Ptest2
2126  Mfng=1/(1+(1/Vfng-1)*Mwv/28.97)
2127  Mfng=Mfng*100
2128  Vfng=Vfng*100
2131  BEEP
2134  IF Iov=2 THEN
2137     PRINT
```

```
2138!    RECORD TIME OF TAKING DATA
2139     IF Im=1 THEN
2140        OUTPUT 709;"TD"
2141        ENTER 709;Told$
2142     END IF
2144     PRINT USING "10X,""Data set number           = "",DD,4X,14A";J,Told$
2145     OUTPUT 709;"AR AF40 AL40 VR5"
2146     OUTPUT 709;"AS 5A"
2149  END IF
2152  IF Iov=2 AND Ng=1 THEN
2155     PRINT USING "10X,""   Psat     Ptran    Tmeas     Tsat         NG %"""
2158     PRINT USING "10X,""  (kPa)    (kPa)      (C)      (C)        Molal """
2161   PRINT USING "11X,1(3D.DD,2X),1(3D.DD,3X),2(3D.DD,2X),2X,1(M3D.D,2X)":Pks,
Pkp,Tsteam,Tsat,Mfng
2164     PRINT
2167  END IF
2170  IF Mfng .5 THEN
2173     BEEP
2176     IF Im=1 AND Ng=1 THEN
2179        BEEP
2182        PRINT
2185        PRINT USING "10X,""Energize the vacuum system """
2188        BEEP
2191        INPUT "OK TO ACCEPT THIS RUN (1=Y,0=N)?",Ok
2194        IF Ok=0 THEN
2197           BEEP
2200           DISP "NOTE: THIS DATA SET WILL BE DISCARDED!! "
2203           WAIT 5
2206           GOTO 1780
2209        END IF
2212     END IF
2215  END IF
2218  IF Im=1 THEN
2221     IF Fm<10 OR Fm>100 THEN
2224        Ifm=0
2227        BEEP
2230        INPUT "INCORRECT FM (1=ACCEPT,0=DELETE)",Ifm
2233        IF Ifm=0 THEN 1804
2236     END IF
2239  END IF
2242! ANALYSIS BEGINS
2243  IF Istu=0 THEN
2252     T11=FNTvsV58(Emf(3))
2262     T12=FNTvsV55(Emf(5))
2272     To1=FNTvsV58(Emf(4))
2282     To2=FNTvsV55(Emf(6))
```

```
2292      T11=T11-273.15
2302      T12=T12-273.15
2312      To1=To1-273.15
2322      To2=To2-273.15
2332      Tdel1=To1-T11
2342      Tdel2=To2-T12
2352      Tdel3=T2-T1
2353      Etp1=Emf(3)+Etp/20.
2354      Dtde=2.5931E-2-1.50464E-5*Etp1+1.21701E-10*Etp1^2-5.1164E-15*Etp1^3+3.2
201E-19*Etp1^4
2355      Tris=Dtde*Etp/10.
2358      To3=T11+Tris
2359      IF Iov=2 THEN
2361         PRINT USING "1X,""  TIN1    TOUT1    TIN3    TOUT3    DELT1    DELT3    T
PILE  """
2362         PRINT USING "1X,""    (TEFLON)          (QUARTZ) """
2364         PRINT USING "2X,7(3D.DD,2X)";T11,To1,T1,T2,Tdel1,Tdel3,Tris
2365      END IF
2367      Er1=ABS(T11-T1)
2368      Er3=ABS(T12-T1)
2369      PRINTER IS 1
2370      BEEP
2375      Er2=ABS((T2-T1)-(Tris))/(T2-T1)
2377      IF Er2 .05 AND Im=1 THEN
2378         BEEP
2379         PRINT "QCT AND T-PILE DIFFER BY MORE THAN 5%"
2380         Ok2=1
2381         IF Ok2=0 AND Er2 .05 AND Im=1 THEN 1780
2382      END IF
2383      PRINTER IS 701
2384   ELSE
2385      T1=FNTsv(Emf(2))
2386      Grad=FNGrad((T1+T2)*.5)
2387      To=T1+ABS(Etp)/(10*Grad)*1.E+6
2388      T11=T1
2389      To3=To
2391   END IF
2392   IF Istu=0 AND Itm=0 THEN
2393      T1i=T11
2394      T2o=To1
2395   END IF
2396   IF Itm=1 THEN
2397      T1i=T1
2398      T2o=T2
2399   END IF
2400   IF Itm=2 THEN
```

```
2401      T1i=T11
2402      T2o=To3
2403    END IF
2404    Tavg=(T1i+T2o)*.5
2405    Ift=0
2406    Cpw=FNCpw(Tavg)
2407    Rhow=FNRhow(Tavg)
2408    IF Istu=0 THEN
2410       Md=(6.7409*Fm+13.027)/1000.
2411       Md=Md*(1.0365-1.96644E-3*T1i+5.252E-6*T1i^2)/1.0037
2412    ELSE
2413       Md=1.04805E-2+6.80932E-3*Fm
2414       Md=Md*(1.0365-1.96644E-3*T1i+5.252E-6*T1i^2)/.995434
2415    END IF
2417    Mf=Md/Rhow
2418    Vw=Mf/(PI*Di^2/4)
2419    Vws=Vw*(Di/1.27E-2)^2
2420    Tcor=FNTfric(T2o)
2444    T2o=Tcor
2445    Q=Md*Cpw*(T2o-T1i)
2446    Qp=Q/(PI*Do*L)
2447    Ift=0
2448    Kw=FNKw(Tavg)
2449    Muw=FNMuw(Tavg)
2450    Rei=Rhow*Vw*Di/Muw   ! ASSUMED SAME FOR KORODENSE
2451    Prw=FNPrw(Tavg)
2452    Fe1=0.
2453    Fe2=0.
2454    Cf=1.
2455    Prwf=Prw
2456    Reif=Rei
2461    IF Ihi=0 THEN
2462       Ome=Rei^Re.p*Prw^.3333*Cf
2465    END IF
2466    IF Ihi=1 THEN
2467       Sra=.88-(.24/(4.+Prwf))
2468       Srb=.333333+.5*EXP(-.6*Prwf)
2470       Ome=(5.+.015*Reif^Sra*Prwf^Srb)
2471    END IF
2472    IF Ihi=2 THEN
2473       Epsi=(1.82*LGT(Rei)-1.64)^(-2)
2474       Ppk1=1.+3.4*Epsi
2475       Ppk2=11.7+1.8*Prw^(-1/3)
2476       Pp1=(Epsi/8)*Rei*Prw
2477       Pp2=(Ppk1+Ppk2*(Epsi/8)^.5*(Prw^.6666-1))
2478       Ome=Pp1/Pp2
```

```
2479  END IF
2481  H1=Rw/D1*G1*Gme
2482  IF Ife=0 THEN GOTO 2491
2483  P1=PI*(Do+D1)
2484  A1=(D1-D1)*PI*(D1+D1 *.5
2485  M1=(H1*P1/(Kcu*A1))^.5
2486  P2=PI*(D1+D2)
2487  A2=(D2-D1)*PI*(D1+D2 *.5
2488  M2=(H1*P2/(Kcu*A2))^.5
2489  Fe1=FNTanh(M1*L1)/(M1*L1)
2490  Fe2=FNTanh(M2*L2)/(M2*L2)
2491  Dt=Q/(PI*D1*(L+L1*Fe1+L2*Fe2)*H1)
2492  IF Ih1=0 THEN
2494     Cfc=(Muw/FNMuw(Tavg+Dt/2))^.14
2495     IF ABS((Cfc-Cf)/Cfc) .001 THEN
2497        Cf=(Cf+Cfc)*.5
2500        GOTO 2461
2501     END IF
2503  END IF
2504  IF Ih1=1 THEN
2505     Prwfc=FNPrw(Tavg+Dt)
2506     Re1fc=Vw*D1*FNRhow(Tavg+Dt)/FNMuw(Tavg+Dt)
2507     IF ABS((Prwfc-Prwf)/Prwfc)>.001 OR ABS((Re1fc-Re1f)/Re1fc)>.001 THEN
2508        Prwf=(Prwfc+Prwf)/2.
2509        Re1f=(Re1fc+Re1f)/2.
2510        GOTO 2461
2511     END IF
2513  END IF
2516  Ift=Ifto
2517  Lmtd=(T2o-T11)/LOG((Tsteam-T11)/(Tsteam-T2o))
2518  Uo=Q/(Lmtd*PI*Do*L)
2519  Ho=1/(1/Uo-Do*L/(D1*(L+L1*Fe1+L2*Fe2)*H1)-Rm)
2520  Tcf=Qp/Ho
2521  Cpsc=FNCpw((Tcon+Tsteam)*.5)
2522  Hfg=FNHfg(Tsteam)
2524  Two=Tsteam-Qp/Ho
2527  Tf1lm=Tsteam/3+Two*2/3
2530  Kf=FNKw(Tf1lm)
2533  Rhof=FNRhow(Tf1lm)
2536  Muf=FNMuw(Tf1lm)
2539  Hpq=.651*Kf*(Rhof^2*9.81*Hfg/(Muf*Do*Qp))^.3333
2541  Hnuss=.728*(Kf^3*9.81*Hfg*Rhof^2/(Muf*Do*Tcf))^.25
2542  Alp1=.728*Ho/Hnuss
2548  Tfm(J-1)=Tf1lm
2551  Qpa(J-1)=Qp
2554  Y=Hpq*Qp^.3333
```

```
2557   q=Qp
2560   Sx=Sx+X
2563   Sy=Sy+Y
2566   Sxs=Sxs+X^2
2569   Sxy=Sxy+X*Y
2572   Q1=500
2575   Qloss=Q1/(100-25)*(Tsteam-Troom)  ' TO BE MODIFIED
2578   Hfc=FNHf(Tcon)
2584   Mdv=0
2587   Bp=(Bvol*100)^2/5.76
2590   Hsc=Cpsc*(Tsteam-Tcon)
2593   Mdvc=((Bp-Qloss)-Mdv*Hsc)/Hfg
2596   IF ABS((Mdv-Mdvc)/Mdvc) .01 THEN
2599      Mdv=(Mdv+Mdvc)*.5
2602      GOTO 2593
2605   END IF
2608   Mdv=(Mdv+Mdvc)*.5
2611   Vg=FNVvst(Tsteam)
2614   Vv=Mdv*Vg/Ax
2620   F=(9.81*Do*Muf*Hfg)/(Vv^2*Kf*(Tsteam-Two))
2623   Nu=Ho*Do/Kf
2626   Ret=Vv*Rhof*Do/Muf
2629   Nr=Nu/Ret^.5
2630   Hfuj=.96*(9.81*Hfg/Tcf)^.2*Kf^.8*Vv^.1*Rhof^.5/(Do*Muf)^.3
2635   IF Iov=2 THEN
2645      PRINT
2647      PRINT USING "5X,"" Vw       Re1          H1          Uo          Hfuj(DT)
      Hnu(Q)"""
2650      PRINT USING "5X,Z.DD,1X,3(MZ.3DE,1X),3X,2(MZ.3DE,3X)";Vw,Re1,H1,Uo,Hfuj
,Hpq
2651      PRINT
2653      PRINT USING "5X,"" Vv       Ho          q           Tcf       NuRe       F
      Hnu(DT)"""
2655      PRINT USING "5X,Z.DD,1X,2(MZ.3DE,1X),2X,3D.DD,2X,3(MZ.3DE,1X)";Vv,Ho,Qp
,Tcf,Nr,F,Hnuss
2656      PRINT
2658   END IF
2659   IF Iov=1 THEN
2660     IF Ih1=1 THEN
2661      PRINT USING "11X,DD,2X,Z.DD,1X,3(MD.3DE,1X),2(3D.DD,1X),D.DDD";J,Vw,Uo,
Ho,Qp,Tcf,Tsteam,Sra
2662     ELSE
2668    PRINT USING "11X,DD,4X,Z.DD,2X,2(MD.3DE,2X),Z.3DE,3X,3D.DD,2X,3D.DD";J,Vw
,Uo,Ho,Qp,Tcf,Tsteam
2671     END IF
2674   END IF
```

```
2675  IF Im=2 THEN
2684     IF  Iwil=0 AND Ijob=1 OR Iwil 0 THEN OUTPUT @Filep;Qp,Ho
2694  END IF
2707  BEEP
2708  IF Im=1 THEN
2709     IF  Iwil=0 AND Ijob=1 OR Iwil=1 THEN OUTPUT @Filep;Qp,Ho
2711     INPUT "CHANGE TCOOL RISE? 1=Y, 2=N",Itr
2712     IF Itr=1 THEN GOTO 2384
2713     BEEP
2715     INPUT "OK TO STORE THIS DATA SET (1=Y,0=N)?",Oks
2716     IF Oks=1 THEN
2725        OUTPUT @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(*)
2735        Alp2=Alp1+Alp2
2749     ELSE
2752        J=J-1
2755     END IF
2758     BEEP
2761     INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
2764     Nrun=J
2767     IF Go_on  0 THEN Repeat
2770  ELSE
2773     IF J Nrun THEN Repeat
2776  END IF
2779  IF Ijob=1 THEN 2809
2782  IF Iwil=0 THEN
2785     ASSIGN @File TO *
2788     Ijob=1
2791     Iwd=1
2797     Im=2
2800     ASSIGN @File TO O_file$
2803     GOTO 1136
2806  END IF
2809  IF Ifg=0 THEN
2812     PRINT
2815     Sl=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxx-Sx^2)
2818     Ac=(Sy-Sl*Sx)/Nrun
2822     PRINT USING "10X,""Least-Squares Line for Ho vs q curve:"""
2824     PRINT USING "10X,""  Slope      = "",MD.4DE";Sl
2827     PRINT USING "10X,""  Intercept  = "",MD.4DE";Ac
2830  END IF
2833  BEEP
2843  INPUT "ENTER SAME TEMPORARY PLOT FILE NAME",Fplot$
2853  ASSIGN @Filep TO P_file$
2863  FOR I=1 TO Nrun
2873     ENTER @Filep;Qp,Ho
2883     Xc=LOG(Qp/Ho)
```

```
2884      Yc=LOG(Qp)
2885      Zx=Zx+Xc
2886      Zx2=Zx2+Xc^2
2887      Zxy=Zxy+Xc*Yc
2888      Zy=Zy+Yc
2889   NEXT I
2890   Bb=.75
2891   Aa=EXP((Zy-Bb*Zx)/Nrun)
2892   PRINT
2893   PRINT USING "10X,""Least-squares line for q = a*delta-T^b"""
2894   PRINT USING "12X,""a = "",MZ.4DE";Aa
2895   PRINT USING "12X,""b = "",MZ.4DE";Bb
2896   IF Ift=0 THEN
2897      IF Ipc=0 THEN
2898         Qps=2.5E+5
2899         IF Iic=0 THEN Hop=9326
2902         IF Iic=1 THEN Hop=10165*(.01905/Do)^.33333
2905      END IF
2908      IF Ipc=1 THEN
2911         Qps=7.5E+5
2914         IF Iic=0 THEN Hop=7176
2917         IF Iic=1 THEN Hop=7569*(.01905/Do)^.33333
2920      END IF
2923      Hos=Aa^(1/Bb)*Qps^((Bb-1)/Bb)
2926      IF Ipc=0 THEN Aas=2.32E+4
2929      IF Ipc=1 THEN Aas=2.59E+4
2930      Alpsm=.876    !SWENSEN DATA
2931      IF Iwil=0 THEN GOTO 2959
2933      Enrat=Alp2/Alpsm
2934      Enr=Hos/Hop
2938      PRINT
2947      PRINT USING "12X,""Enhancement ratio (Del-T) =  "",2D.3D";Enrat
2956   ELSE
2959      PRINT
2962      IF Ift=1 THEN
2965         Aas=2687.2   ! ZEBROWSKI (V = 0.4 m/s)
2968         Aas=2557.0*(.01905/Do)^.33333   ! VAN PETTEN (V = 0.25 m/s)
2971      END IF
2974      IF Ift=2 THEN Aas=9269.7*(.01905/Do)^.33333
2977      Edt=Aa/Aas
2980      Eq=Edt^(4/3)
2989   END IF
2995      BEEP
2998      PRINT
3001      PRINT USING "10X,""NOTE: "",ZZ,"" data points were stored in file "",10
A";J,D_file$
```

```
3007  BEEP
3013  PRINT
3016  PRINT USING "13X,  NOTE: "",ZZ,"" X-Y pairs were stored in data file '",10
A";J,Plot$
3031  BEEP
3073  ASSIGN @File TO *
3079  ASSIGN @Filep TO *
3080  PURGE "DUMMY"
3100  IF Iso=3 THEN CALL Wilson(C1)
3116  END
3118  DEF FNPvst(Tc)
3121  COM /Fld/ Ift,Istu
3124  DIM K(8)
3127  IF Ift=0 THEN
3130     DATA -7.691234564,-26.08023696,-168.1706546,64.23285504,-118.9646225
3133     DATA 4.16711732,20.9750676,1.E9,6
3136     READ K(*)
3139     T=(Tc+273.15)/647.3
3142     Sum=0
3145     FOR N=0 TO 4
3148        Sum=Sum+K(N)*(1-T)^(N+1)
3151     NEXT N
3154     Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
3157     Pr=EXP(Br)
3160     P=22120000*Pr
3163  END IF
3166  IF Ift=1 THEN
3169     Tf=Tc*1.8+32+459.6
3172     P=10^(33.0655-4330.98/Tf-9.2635*LGT(Tf)+2.0539E-3*Tf)
3175     P=P*101325/14.696
3178  END IF
3181  IF Ift=2 THEN
3184     A=9.394685-3066.1/(Tc+273.15)
3187     P=133.32*10^A
3190  END IF
3193  RETURN P
3196  FNEND
3199  DEF FNHfg(T)
3202  COM /Fld/ Ift,Istu
3205  IF Ift=0 THEN
3208     Hfg=2477200-2450*(T-10)
3211  END IF
3214  IF Ift=1 THEN
3217     Tf=T*1.8+32
3220     Hfg=7.0557857E+1-Tf*(4.838052E-2+1.2619048E-4*Tf)
3223     Hfg=Hfg*2326
```

```
3226  END IF
3229  IF Ift=2 THEN
3232     Tk=T+273.15
3235     Hfg=1.35264E+6-Tk*(6.38263E+2+Tk*.747462)
3238  END IF
3241  RETURN Hfg
3244  FNEND
3247  DEF FNMuw(T)
3250  COM /Fld/ Ift,Istu
3253  IF Ift=0 THEN
3256     A=247.8/(T+133.15)
3259     Mu=2.4E-5*10^A
3262  END IF
3265  IF Ift=1 THEN
3268     Mu=8.9629819E-4-T*(1.1094609E-5-T*5.566829E-8)
3271  END IF
3274  IF Ift=2 THEN
3277     Tk=1/(T+273.15)
3280     Mu=EXP(-11.0179+Tk*(1.744E+3-Tk*(2.80335E+5-Tk*1.12661E+8)))
3283  END IF
3286  RETURN Mu
3289  FNEND
3292  DEF FNVvst(Tt)
3295  COM /Fld/ Ift,Istu
3298  IF Ift=0 THEN
3301     P=FNPvst(Tt)
3304     T=Tt+273.15
3307     X=1500/T
3310     F1=1/(1+T*1.E-4)
3313     F2=(1-EXP(-X))^2.5*EXP(X)/X^.5
3316     B=.0015*F1-.000942*F2-.0004882*X
3319     K=2*P/(461.52*T)
3322     V=(1+(1+2*B*K)^.5)/K
3325  END IF
3328  IF Ift=1 THEN
3331     Tf=Tt*1.8+32
3334     V=13.955357-Tf*(.16127262-Tf*5.1726190E-4)
3337     V=V/16.018
3340  END IF
3343  IF Ift=2 THEN
3346     Tk=Tt+273.15
3349     P=FNPvst(Tt)
3352     V=133.95*Tk/P
3355  END IF
3358  RETURN V
3361  FNEND
```

```
3364  DEF FNCpw(T)
3367  COM /Fld/ Ift,Istu
3370  IF Ift=0 THEN
3373     Cpw=4.2112093E3-T*(2.68826E-3-T*(4.42361E-5+2.71428E-7*T))
3376  END IF
3379  IF Ift=1 THEN
3382     Cpw=9.2507273E-1+T*(8.3400433E-4+1.7207782E-6*T)
3385  END IF
3388  IF Ift=2 THEN
3391     Tk=T+273.15
3394     Cpw=4.1868*(1.6884E-2+Tk*(3.35083E-3-Tk*(7.224E-6-Tk*7.61748E-9)))
3397  END IF
3400  RETURN Cpw*1000
3403  FNEND
3406  DEF FNRhow(T)
3409  COM /Fld/ Ift,Istu
3412  IF Ift=0 THEN
3415     Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
3418  END IF
3421  IF Ift=1 THEN
3424     Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3)
3427  END IF
3430  IF Ift=2 THEN
3433     Tk=T+273.15-338.15
3436     Vf=9.24848E-4+Tk*(6.2786E-7+Tk*(9.2444E-10+Tk*3.057E-12))
3439     Ro=1/Vf
3442  END IF
3445  RETURN Ro
3448  FNEND
3451  DEF FNPrw(T)
3454  Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
3457  RETURN Prw
3460  FNEND
3463  DEF FNKw(T)
3466  COM /Fld/ Ift,Istu
3469  IF Ift=0 THEN
3472     X=(T+273.15)/273.15
3475     Kw=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
3478  END IF
3481  IF Ift=1 THEN
3484     Kw=8.2095238E-2-T*(2.2214286E-4+T*2.3809524E-8)
3487  END IF
3490  IF Ift=2 THEN
3493     Tk=T+273.15
3496     Kw=4.1868E-4*(519.442+.320920*Tk)
3499  END IF
```

```
3502  RETURN Kw
3505  FNEND
3508  DEF FNTann(X
3511  P=EXP(X)
3514  Q=EXP(-X)
3517  Tann=(P-Q)/(P+Q)
3520  RETURN Tann
3523  FNEND
3526  DEF FNTvsv(V)
3529  COM /Cc/ C(7)
3532  T=C(0)
3535  FOR I=1 TO 7
3538     T=T+C(I)*V^I
3541  NEXT I
3547  RETURN T
3550  FNEND
3553  DEF FNHf(T)
3556  COM /Fld/ Ift,Istu
3559  IF Ift=0 THEN
3562     Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
3565  END IF
3568  IF Ift=1 THEN
3571     Tf=T*1.8+32
3574     Hf=8.2078571+Tf*(.19467857+Tf*1.3214286E-4)
3577     Hf=Hf*2.326
3580  END IF
3583  IF Ift=2 THEN
3586     Hf=250  ! TO BE VERIFIED
3589  END IF
3592  RETURN Hf*1000
3595  FNEND
3598  DEF FNGrad(T)
3601  Grad=37.9853+.104388*T
3604  RETURN Grad
3607  FNEND
3610  DEF FNTvsp(P)
3613  Tu=190
3616  Tl=10
3619  Ta=(Tu+Tl)*.5
3622  Pc=FNPvst(Ta)
3625  IF ABS((P-Pc)/P)>.0001 THEN
3628     IF Pc<P THEN Tl=Ta
3631     IF Pc>P THEN Tu=Ta
3634     GOTO 3619
3637  END IF
3640  RETURN Ta
```

```
6643  FNEND
6646  DEF FNSigma(T)
6649  X=647.3-T-273.16
6652  S=.1160936807*(1+.33*X+1.121404688E-3*X^2-5.75290518E-6*X^3+1.28627465E-8*X^4-1
.14971929E-11*X^5
6655  RETURN S*.001*X^2
6658  FNEND
6826  SUB Wilson(Ci)
6829  COM /Wil/ Nrun,Itm,Iwth,Imc,Ife,Ijob,Iwd,Ifg,Ipco,Ifto,Iwil,Ihi,Ioc,Inam,P
cu,Rexp,Rm,Ax
6832  COM /Fld/ Ift,Istu
6833  COM /Geom/ D1,D2,Di,Do,L,L1,L2
6834  COM /Fric/ Istuo,Inn,Iwtho,Vw,Vws,Inamo
6836  DIM Emf(20),Bvo(42),Bam(42),Eata(42),Ear(42,7),Fma(42),T1a(42),T2a(42)
6845  IF Ioc=0 THEN
6847     PRINT USING "16X,'""Nusselt theory is used for Ho""'"
6848  ELSE
6849     PRINT USING "16X,'""Fujii correlation used for Ho""'"
6850  END IF
6853  BEEP
6856  INPUT "RE-ENTER DATA FILE BEING PROCESSED",D_file$
6859  BEEP
6862  INPUT "GIVE A NAME FOR XY PLOT-DATA FILE",Plot$
6865  CREATE BDAT Plot$,10
6868  ASSIGN @Io_path TO Plot$
6871  Jj=0
6874  ASSIGN @File TO D_file$
6877  ENTER @File;Ifg,Inn
6878  IF Istu=0 THEN
6883     ENTER @File;Ddd,Ddd,Ddd,Ddd
6884  ELSE
6885     IF Ifg=0 THEN ENTER @File;Iwt
6886     IF Ifg=1 THEN ENTER @File;Fp,Fw,Fh
6887  END IF
6888  IF Jj=0 THEN
6895     IF Ihi=0 THEN Ci=.027
6896     IF Ihi=1 THEN Ci=1.00
6897     IF Ihi=2 THEN Ci=1.00
6899     IF Ifg=0 THEN Alp=1.2
6900     IF Ifg=1 THEN Alp=2.6
6901     IF Ift=2 AND Ifg=1 THEN Alp=5.0
6904  END IF
6907  J=0
6910  Sx=0
6913  Sy=0
6916  Sxs=0
```

```
6919   Ixy=0
6922  ! READ DATA FROM A USER-SPECIFIED FILE IF INPUT MODE (Im) = 2
6925   IF Jj=0 THEN
6928      IF Istu=0 THEN
6931         ENTER @File;Bvol,Bamp,Etp,Fm,T1,T2,Ddd,Ddd,Emf(*)
6932      ELSE
6934         ENTER @File;Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),F
m,T1,T2,Phg,Pwater
6936      END IF
6938      Bvo(J)=Bvol
6939      Bam(J)=Bamp
6940      Eata(J)=Etp
6943      Ear(J,0)=Emf(0)
6946      Ear(J,1)=Emf(1)
6949      Ear(J,2)=Emf(2)
6952      Ear(J,3)=Emf(3)
6955      Ear(J,4)=Emf(4)
6956      IF Istu=1 THEN GOTO 6961
6958      Ear(J,5)=Emf(5)
6959      Ear(J,6)=Emf(6)
6960      Ear(J,7)=Emf(7)
6961      Fma(J)=Fm
6962      T1a(J)=T1
6964      T2a(J)=T2
6967   ELSE
6970      Bvol=Bvo(J)
6973      Bamm=Bam(J)
6976      Etp=Eata(J)
6979      Emf(0)=Ear(J,0)
6982      Emf(1)=Ear(J,1)
6985      Emf(2)=Ear(J,2)
6988      Emf(3)=Ear(J,3)
6991      Emf(4)=Ear(J,4)
6992      IF Istu=1 THEN GOTO 6997
6994      Emf(5)=Ear(J,5)
6995      Emf(6)=Ear(J,6)
6996      Emf(7)=Ear(J,7)
6997      Fm=Fma(J)
6998      T1=T1a(J)
7000      T2=T2a(J)
7003   END IF
7004   IF Istu=0 THEN
7006      Tsat=FNTvsv57((Emf(0)+Emf(1))/2.)
7007      Tsat=Tsat-273.15
7009      Ti=FNTvsv58(Emf(3))
7010      To1=FNTvsv58(Emf(4))
```

```
7012      T1=T1-273.15
7013      Tol=Tol-273.15
7015      Etp1=Emf(2)*Etp/20.
7016      Dtde=2.583E-2-1.52464E-5*Etp1+1.21701E-8*Etp1^2-5.1164E-15*Etp1^3+3.2
201E-19*Etp1^4
7017      Trise=Dtde*Etp/10.
7018      To=T1+Trise
7019   ELSE
7020      Tsat=FNTvsv(Emf(0))
7021      T1=FNTvsv(Emf(2))
7022      Grad=FNGrad((T1+T2)*.5)
7023      To=T1+ABS(Etp)/(10*Grad)*.E+6
7024   END IF
7025   CALCULATE THE LOG-MEAN-TEMPERATURE DIFFERENCE
7026   IF Istu=0 AND Itm=0 THEN
7027      Tf=T1
7028      T1=Tol
7029   END IF
7030   IF Itm=1 THEN
7031      Tf=T1
7032      T1=T2
7033   END IF
7034   IF Itm=2 THEN
7035      Tf=T1
7036      T1=To
7038   END IF
7039   Tavg=(Tf+T1)*.5
7040   Trise=T1-Tf
7041   Lmtd=Trise/LOG((Tsat-Tf)/(Tsat-T1))
7042   Ift=0
7043   Cpw=FNCpw(Tavg)
7044   Rhow=FNRhow(Tavg)
7045   Kw=FNKw(Tavg)
7048   Muwa=FNMuw(Tavg)
7051   Prw=FNPrw(Tavg)
7054   Ift=Ifto
7055   IF Istu=0 THEN
7057      Mdt=(6.7409*Fm+13.027)/1000.
7060      Md=Mdt*(1.0365-Tf*(1.96644E-3-Tf*5.252E-6))/1.0037
7061   ELSE
7062      Mdt=1.04805E-2+6.80932E-3*Fm
7063      Md=Mdt*(1.0365-Tf*(1.96644E-3-Tf*5.252E-6))/.995434
7065   END IF
7066   Vf=Md/Rhow
7067   Vw=Vf/(PI*D1^2/4)
7068   Jws=Vw*(D1/1.27E-2)^2
```

```
7069  Tcor=FNTfric(Trise)
7070  Trise=Tcor
7071  Tcon=FNTvsv58(Emf(7))
7072  Tcon=Tcon-273.15
7074  Cpsc=FNCpw((Tcon+Tsat)*.5)
7076  Hfg=FNHfg(Tsat)
7078  Q1=500
7080  Qloss=Q1/(100-25)*(Tsat-Troom)  ' TO BE MODIFIED
7082  Mdv=0
7084  Bp=(Bvol*100)^2/5.75
7085  Hsc=Cpsc*(Tsat-Tcon)
7086  Mdvc=((Bp-Qloss)-Mdv*Hsc)/Hfg
7088  IF ABS((Mdv-Mdvc)/Mdvc)>.01 THEN
7090     Mdv=(Mdv+Mdvc)*.5
7092     GOTO 7086
7094  END IF
7096  Mdv=(Mdv+Mdvc)*.5
7098  Vg=FNVvst(Tsat)
7100  Vv=Mdv*Vg/Ax
7108  Q=Md*Cpw*Trise
7111  Qp=Q/(PI*Do*L)
7114  Uo=Qp/Lmtd
7117  Re=Rhow*Vw*Di/Muwa
7120  Fe1=0
7123  Fe2=0
7126  Cf=1.
7127  Prwf=Prw
7128  Re1f=Re
7129  Ift=0
7131  Two=Tsat-5
7132  Tf1lm=Tsat/3+Two*2/3
7135  Kf=FNKw(Tf1lm)
7138  Rhof=FNRhow(Tf1lm)
7141  Muf=FNMuw(Tf1lm)
7144  Hfgp=FNHfg(Tsat)+.68*FNCpw(Tf1lm)*(Tsat-Two)
7147  New=Kf*(Rhof^2*9.81*Hfgp/(Muf*Do*Qp))^.3333
7148  New=(Kf^3*9.81*Hfgp*Rhof^2/(Muf*Do*(Tsat-Two)))^.25
7150  IF Ioc=1 THEN
7153     New=Kf*((9.81*Hfgp/Qp)^.25)*((Muf*Do)^(-.375))*(Rhof^.625)*(Vv^.125)
7154     New=(9.81*Hfgp/(Tsat-Two))^.2*Kf^.8*Vv^.1*Rhof^.5/(Do*Muf)^.3
7156  END IF
7159  Ho=Alp*New
7162  Twoc=Tsat-Qp/Ho
7165  IF ABS((Twoc-Two)/Twoc)>.001 THEN
7168     Two=Twoc
7171     GOTO 7132
```

```
7174  END IF
7175  Re.p1=Re.p
7184  IF Ih1=0 THEN
7186     Omega=Re^.Re.p1*Prw^.3333*Cf
7187  END IF
7188  IF Ih1=1 THEN
7189     Sra=.88-(.24/(4.+Prwf))
7190     Srb=.333333+.5*EXP(-6*Prwf)
7191     Omega=(5.+.015*Re1f^Sra*Prwf^Srb)
7192  END IF
7193  IF Ih1=2 THEN
7194     Eps1=(1.82*LGT(Re)-1.64)^(-2)
7195     Pph1=1.+3.4*Eps1
7196     Pph2=11.7+1.8*Prw^(-1/3)
7197     Pp1=(Eps1/8)*Re*Prw
7198     Pp2=(Pph1+Pph2*(Eps1/8)^.5*(Prw^.6666-1))
7199     Omega=Pp1/Pp2
7200  END IF
7202  H1=Kw/D1*C1*Omega
7203  IF Ife=0 THEN 7216
7204  P1=PI*(D1+D1)
7205  P2=PI*(D1+D2)
7206  A1=(D1-D1)*PI*(D1+D1)*.5
7207  A2=(D2-D1)*PI*(D1+D2)*.5
7208  M1=(H1*P1/(Kcu*A1))^.5
7209  M2=(H1*P2/(Kcu*A2))^.5
7210  Fe1=FNTanh(M1*L1)/(M1*L1)
7213  Fe2=FNTanh(M2*L2)/(M2*L2)
7216  Dt=Q/(PI*D1*(L+L1*Fe1+L2*Fe2)*H1)
7217  IF Ih1=0 THEN
7219     Muw1=FNMuw(Tavg+Dt)
7222     Cfc=(Muwa/Muw1)^.14
7225     IF ABS((Cfc-Cf)/Cfc)>.001 THEN
7228        Cf=(Cf+Cfc)*.5
7231        GOTO 7184
7232     END IF
7234  END IF
7235  IF Ih1=1 THEN
7236     Prwfc=FNPrw(Tavg+Dt)
7237     Re1fc=Vw*D1*FNRhow(Tavg+Dt)/FNMuw(Tavg+Dt)
7239     IF ABS((Prwfc-Prwf)/Prwfc)>.001 OR ABS((Re1fc-Re1f)/Re1fc)>.001 THEN
7240        Prwf=(Prwfc+Prwf)/2.
7241        Re1f=(Re1fc+Re1f)/2.
7242        GOTO 7184
7243     END IF
7245  END IF
```

```
7246  Ift=Ifto
7247  x=Do*New*L/(Omega*Kw*(L+L1*Fe1+L2*Fe2))
7248  y=New*(1/Uo-Fm)
7249! COMPUTE COEFFICIENTS FOR THE LEAST-SQUARES-FIT STRAIGHT LINE
7250  IF Jp=1 THEN OUTPUT @Io_path;X,Y
7252  Sx=Sx+x
7255  Sy=Sy+y
7258  Sxs=Sxs+X*X
7261  Sxy=Sxy+X*Y
7264  IF Im=1 AND Jj=0 THEN OUTPUT @File;Bvol,Bamp,Etp,Fm,T1,T2,Pvap1,Pvap2,Emf(
*)
7267  J=J+1
7270  IF J Nrun THEN 6925
7273  S1=(Nrun*Sxy-Sy*Sx)/(Nrun*Sxs-Sx^2)
7276  IF Iw1=2 THEN
7277     IF Ih1=0 THEN S1=1/.027
7283     IF Ih1=1 THEN S1=1/1.00
7289     IF Ih1=2 THEN S1=1/1.00
7291  END IF
7294  Ac=(Sy-S1*Sx)/Nrun
7297  C1c=1/S1
7300  Alpc=1/Ac
7303  Jj=Jj+1
7306  IF Jp=1 THEN Jp=2
7309  Cerr=ABS((C1c-C1)/C1c)
7312  Aerr=ABS((Alpc-Alp)/Alpc)
7315  IF Cerr .001 OR Aerr .001 THEN
7318     C1=(C1c+C1)*.5
7321     Alp=(Alpc+Alp)*.5
7324     BEEP
7327     IF Ijob=1 THEN 6907
7330  ELSE
7333     IF Jp=0 THEN Jp=1
7336  END IF
7339  IF Jp=1 THEN 6874
7342  C1=(C1+C1c)*.5
7345  PRINT
7346  IF Ih1=0 THEN
7348     PRINT USING "10X,""C1 (based on Sieder-Tate)       =  "",Z.4D";C1
7349  END IF
7350  IF Ih1=1 THEN
7351     PRINT USING "10X,""C1 (based on Sleicher-Rouse)    =  "",Z.4D";C1
7352!    PRINT USING "10X,""Re exponent for Sleicher-Rouse  =  "",D.DDD";Sra
7353  END IF
7354  IF Ih1=2 THEN
7355     PRINT USING "10X,""C1 (based on Petukhov-Popov)    =  "",Z.4D";C1
```

```
7356  END IF
7357  IF Ipc=0 THEN
7358     PRINT USING "10X,""Alpha (based on Nusselt (Tdel)) = "",Z.4D";Alp
7359  END IF
7360  IF Ipc=1 THEN
7361     PRINT USING "10X,""Alpha (based on Fujii (Tdel)) = "",Z.4D";Alp
7362  END IF
7363  IF Inam=5 OR Inam=6 THEN
7364     IF Ins=0 THEN
7365        IF Ipco=0 AND Inn=0 THEN Alpsm=.8218  !NO INSERT,VACUUM,S-T
7367        IF Ipco=1 AND Inn=0 THEN Alpsm=.7793  !NO INSERT,ATMOSPHERIC,S-T
7368        IF Ipco=0 AND Inn=3 THEN Alpsm=.7854  !HEATEX,VACUUM,S-T
7369        IF Ipco=1 AND Inn=3 THEN Alpsm=.7769  !HEATEX,ATMOSPHERIC,S-T
7371     END IF
7372     IF Ins=1 THEN
7373        IF Ipco=0 AND Inn=0 THEN Alpsm=.8613  !NO INSERT,VACUUM,S-R
7374        IF Ipco=1 AND Inn=0 THEN Alpsm=.8218  !NO INSERT,ATMOSPHERIC,S-R
7375        IF Ipco=0 AND Inn=3 THEN Alpsm=.7791  !HEATEX,VACUUM,S-R
7376        IF Ipco=1 AND Inn=3 THEN Alpsm=.7929  !HEATEX,ATMOSPHERIC,S-R
7378     END IF
7379     IF Ins=2 THEN
7380        IF Ipco=0 AND Inn=0 THEN Alpsm=.8205  !NO INSERT,VACUUM,P-P
7381        IF Ipco=1 AND Inn=0 THEN Alpsm=.7654  !NO INSERT,ATMOSPHERIC,P-P
7382        IF Ipco=0 AND Inn=3 THEN Alpsm=.7670  !HEATEX,VACUUM,P-P
7383        IF Ipco=1 AND Inn=3 THEN Alpsm=.7708  !HEATEX,ATMOSPHERIC,P-P
7385     END IF
7386  END IF
7387  IF Inam=4 THEN
7390     IF Ipco=1 THEN Alpsm=.876  !SWENSEN DATA BASED ON DEL-T
7391  END IF
7392  IF Inam=0 OR Inam=3 THEN
7393     IF Ipco=0 THEN Alpsm=.83   !VP MISTV103
7394     IF Ipco=1 THEN Alpsm=.88   !VP SMTHSTA65
7397     IF Ift=1 THEN Alpsm=.677   !VAN PETTEN (V = 0.25 m/s)
7399     IF Ift=2 THEN Alpsm=1.262
7399  END IF
7401  IF Inam=1 THEN  !MITROU ALPHA FOR P-P FROM REPROCESSING
7402     IF Ipco=0 THEN Alpsm=.8437
7403     IF Ipco=1 THEN Alpsm=.8418
7404  END IF
7405  Et=Alp/Alpsm
7406  Eq=Et^1.333333
7407  PRINT USING "10X,""Enhancement (q)                    = "",DD.3D";Eq
7408  PRINT USING "10X,""Enhancement (Del-T)                = "",DD.3D";Et
7409  ASSIGN @File TO *
7410  SUBEND
```

```
7721  DEF FNTvsv55(V)
7731  COM /Cc55/ T55(5)
7741  T=T55(0)
7751  FOR I=1 TO 5
7761     T=T+T55(I)*V^I
7771     NEXT I
7781  RETURN T
7791  FNEND
7801  DEF FNTvsv56(V)
7811  COM /Cc56/ T56(5)
7821  T=T56(0)
7831  FOR I=1 TO 5
7841     T=T+T56(I)*V^I
7851  NEXT I
7861  RETURN T
7871  FNEND
7881  DEF FNTvsv57(V)
7891  COM /Cc57/ T57(5)
7901  T=T57(0)
7911  FOR I=1 TO 5
7921     T=T+T57(I)*V^I
7931  NEXT I
7941  RETURN T
7951  FNEND
7961  DEF FNTvsv58(V)
7971  COM /Cc58/ T58(5)
7981  T=T58(0)
7991  FOR I=1 TO 5
8001     T=T+T58(I)*V^I
8011  NEXT I
8021  RETURN T
8031  FNEND
8100  DEF FNTfric(Tcor)
8110  COM /Fric/ Istuo,Inn,Iwtho,Vw,Vws,Inamo
8115  IF Istuo=0 AND Iwtho=0 THEN !SWENSEN FRICTION FAC. FOR COPPER TUBE
8120     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-2.73E-4+1.75E-4*Vw+9.35E-4*Vw^2-1.9
6E-5*Vw^3)
8130     IF Inn=1 THEN Tcor=Tcor-(-6.44E-5+1.71E-3*Vw+4.45E-4*Vw^2+4.07E-5*Vw^3)
8140     IF Inn=2 THEN Tcor=Tcor-(-3.99E-4+2.75E-3*Vw+1.45E-3*Vw^2+8.16E-5*Vw^3)
8150     IF Inn=3 THEN Tcor=Tcor-(8.57E-5+1.23E-3*Vw+1.08E-3*Vw^2+8.16E-5*Vw^3)
8160  END IF
8170  IF Istuo=0 AND Iwtho=2 THEN !OKEEFE FRIC. FAC. FOR SMOOTH TITANIUM TUBE.
8180     IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(-4.62E-5-7.53E-4*Vw+1.80E-3*Vw^2-8.8
4E-5*Vw^3)
8190     IF Inn=3 AND Inamo=5 THEN Tcor=Tcor-(2.09E-4+9.74E-4*Vw+2.12E-3*Vw^2-3.
31E-5*Vw^3)
```

```
8190      IF Inn=3 AND Inamo=6 THEN Tcor=Tcor-(1.9555E-4+3.9721E-3*Vw+3.127E-4*Vw
 2+3.519E-4*Vw^3)
8200   END IF
8210   IF Istuc=0 AND Iwtho=1 THEN !FRICTION FACTORS FOR LPD KORODENSE
8220      IF Inn=0 AND Vw .5 THEN Tcor=Tcor-(-3.386E-4+1.88E-3*Vw+6.013E-4*Vw 2-4
.133E-5*Vw 3)
8230      IF Inn=3 THEN Tcor=Tcor-(2.089E-4+9.202E-4*Vw+1.893E-3*Vw^2-2.781E-5*Vw
^3)
8240   END IF
8242   IF Istuc=0 AND Iwtho=3 THEN !FRICTION FACTORS FOR MHT KORODENSE
8244      IF Inn=0 AND Vw>.5 THEN Tcor=Tcor-(6.79E-5+1.632E-3*Vw+8.409E-4*Vw^2+1.
111E-4*Vw 3)
8246      IF Inn=3 THEN Tcor=Tcor-(2.564E-4+6.263E-4*Vw+2.603E-3*Vw^2+7.830E-6*Vw
 3)
8247   END IF
8250   IF Istuc=1 THEN
8260      IF Inn=0 THEN Tcor=Tcor-(.0138+.001*Vw^2)
8270      IF Inn=1 THEN Tcor=Tcor-.004*Vws^2
8280      IF Inn=2 THEN Tcor=Tcor-.004*Vws^2
8290   END IF
8300   RETURN Tcor
8310   FNEND
```

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